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(FATIGUE OF FOUR STAINLESS STEELS AND THREE TITANIUM ALLOYS BEFORE AND AFTER EXPOSURE TO 550° F (561° K) UP TO 8800 HOURS)

by Walter Illg and Claude B. Castle

Langley Research Center
Langley Station, Hampton, Va.

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THREE TITANIUM ALLOYS BEFORE AND AFTER EXPOSURE

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SUMMARY

Fatigue and tensile sheet specimens of four steels and three titanium alloys were tested before and after exposure to 550° F (561° K) for periods up to 1 year. None of the seven materials exhibited a serious degradation in fatigue life in any of the four specimen configurations used. However, in two cases (Ti-4Al-3Mo-1V spot-welded, Ti-8Al-1Mo-1V edge-notched), a slight but steady life-reduction trend was observed. The static joint efficiencies, prior to exposure, of both spot-welded and fusion-welded specimens were higher for titanium alloys than for steels.

INTRODUCTION

Structural materials located near leading edges of a supersonic transport may reach temperatures as high as 550° F (561° K) due to aerodynamic heating during flight at Mach 3. Since this condition will exist during most of the flying hours throughout the life of the aircraft, the heat environment may affect the long-time load-carrying capacity of the materials of construction. Therefore, ~~an~~ this investigation was conducted ~~is underway~~ to determine effects of exposure to a 550° F (561° K) environment on fatigue strengths of a number of stainless steel and titanium alloys in sheet form. Exposure periods will run up to 30,000 hours. This report presents the results of static and fatigue tests before and after soaking periods up to 1 year (8800 hours). Aircraft construction methods were simulated with various types of specimens including notched and welded configurations. → p9

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units, (SI). Factors relating the two systems are given in reference 1.

e	permanent tensile elongation in given gage length, percent
K_T	theoretical stress concentration factor
N	life of fatigue specimen after exposure to 550° F (561° K), cycles
N_i	life of fatigue specimen before exposure, cycles
S_f	fatigue limit, stress value below which fatigue failure will not occur in 10^7 cycles, ksi (MN/m^2)
S_{max}	maximum nominal stress during a fatigue load cycle, ksi (MN/m^2)
S_{mean}	mean stress during a fatigue load cycle, ksi (MN/m^2)
S_u	static tensile ultimate strength, ksi (MN/m^2)
S_y	static tensile yield strength, 0.2-percent offset, ksi (MN/m^2)
ρ	density, lb/in.^{3} (kg/m^3)

SPECIMENS

Four stainless steels and three titanium alloys were included in this investigation. The steels used were PH 15-7 Mo in the TH 1050 condition, AM 350 in both the double-aged condition (designated AM 350 DA) and the 20-percent cold reduced plus tempered condition (designated AM 350 CRT), and AISI 301 in the full-hard condition (50-percent cold reduction) (designated AISI 301 CR). The titanium alloys used were Ti-4Al-3Mo-1V solution treated and aged, Ti-6Al-4V annealed, and Ti-8Al-1Mo-1V single-annealed. Chemical composition and heat-treating details are given in the appendix.

Three types of fatigue specimens were used to represent widely differing types of stress raisers found in aircraft construction and these types are shown in figure 1. Unnotched specimen tests were also conducted to reveal changes in fatigue strength of the basic material. The edge-notched specimens had a stress concentration factor of 4. This configuration of specimens has been used in a variety of studies of fatigue behavior in aluminum alloys because it has been suggested (ref. 2) that its fatigue behavior is similar to that of contemporary fabricated structures. The relative fatigue behavior among structures made of stainless steels, titanium alloys, and aluminum alloys may be ascertained by comparing the results of the present investigation with data for aluminum alloys. Welded joints were investigated in the spot-weld and fusion-weld form. Symmetrical butt joints were chosen to minimize bending stresses under axial

load. A single row of spot-welds was used for simplicity. The number of spot-welds was designed to obtain maximum strength without short-circuiting the current through adjacent welds. The result was seven spot-welds for the steel specimens and five for the titanium alloy specimens. No filler rod was used for the fusion-welded specimens. Details of fabrication and handling procedures may be found in the appendix.

The static tensile specimens are shown in figure 2. The welded tensile specimen configurations include both transverse and longitudinal welds as recommended in reference 3. The transverse type is useful for determining the strength of welded joints and the longitudinal type is sensitive to a loss in ductility due to welding.

PROCEDURE

Approximately 100 fatigue specimens were fabricated from each material and of each configuration. A number of specimens were tested to establish a pre-exposure S-N curve at room temperature using mean stresses of 40 ksi (276 MN/m^2) and 25 ksi (173 MN/m^2) for steels and titanium alloys, respectively. These mean stresses were considered to be reasonably representative of operating 1g stresses in a supersonic transport. The ratios of mean stress to ultimate strength are between 1/5 and 1/6 or roughly equivalent to the ratios used in contemporary aluminum aircraft.

Sixty fatigue specimens of each type and material were hung on racks in a resistance-heated electric furnace having forced-air circulation. A single standard tensile specimen was included with every 10 fatigue specimens to provide a check on possible deterioration of static strength. The temperature of the furnace was maintained at 550° F (561° K) ± 10° F (5.5° K) and was monitored by a thermocouple welded to a sample specimen.

Specimens were removed from the oven after periods of 2200 hours, 4400 hours, and 8800 hours. Six fusion-weld specimens and five of each of the other configurations were removed each time along with one tensile specimen with each group. Five fatigue specimens were then tested at room temperature at a particular stress level chosen from the preexposure S-N curves. The sixth fusion-weld specimen was tested statically to detect possible changes in tensile strength of the welded specimen due to exposure.

Constant-amplitude fatigue tests were conducted in subresonant-type axial-load fatigue machines which are fully described in reference 4 and are shown in figures 3 and 4. Load was sensed by a weigh-bar in series with the specimen and grips. A wire strain-gage bridge cemented to the weigh-bar supplied a load signal to an oscilloscope which was used to monitor the cyclic loading. Operating frequency was 1800 cycles per minute (30 Hz). The machines were calibrated periodically and a loading accuracy of ±10 pounds (±44 N) was maintained.

RESULTS AND DISCUSSION

Preexposure Static Tests

The tensile properties of standard tensile specimens are given in table I and are within ranges normally expected for these materials. The effects of fusion welding on these properties are presented in table II. For comparison purposes, table II includes the preexposure tensile strength and elongations from table I.

All the steels suffered large losses in tensile ultimate and yield strengths in the as-welded condition. However, when PH 15-7 Mo and AM 350 DA were heat treated after welding instead of before, the strength losses were considerably less. All three titanium alloys were little affected strengthwise by fusion welding. The elongation values of the longitudinally welded specimens, measured after fracture, were smaller than those of virgin specimens for all three titanium alloys and for AM 350 20 percent CRT.

The static strengths of the fatigue specimens are given in table III. These data are compared with those found for standard tensile specimens from table I. The strengths of the unnotched specimens were within 5 percent of the value from standard tensile specimens except for the AM 350 DA which showed an increase of 8 percent. A notch-strengthening effect was found for the $K_T = 4$ specimens except for the AISI 301 where there was a weakening effect and for Ti-4Al-3Mo-1V and AM 350 CRT where no significant effect was noted.

The results of the static tests of spot-welded joints showed that the titanium alloys had higher joint efficiencies than the steels. The joint efficiencies (joint strength divided by material strength) of the titanium alloys with five spot-welds per joint varied from 96 to 99 percent. Those for steels with seven spot-welds per joint varied from 86 to 92 percent. Almost all spot-welded specimens failed through the material immediately adjacent to the heat-affected zones. The exceptions were three Ti-6Al-4V tests and one of two Ti-4Al-3Mo-1V tests wherein failure took place away from the welds.

The joint efficiencies of titanium alloys were also impressive in the fusion-welded configuration. Joint efficiency varied from 101 to 107 percent, whereas for most steels it ranged between 60 and 69 percent. In the case of the two heat-treated steels, their joint efficiencies were nearly 100 percent when the specimens were heat treated after fusion welding instead of before.

Desirable welding characteristics of material for aircraft use would include little or no postweld treatment and little change in strength and elongation values due to welding. Of the materials tested in this program, only the three titanium alloys approached these requirements. Of these three, the welding characteristics of Ti-8Al-1Mo-1V were superior because the Ti-6Al-4V required a postweld moderate temperature stress relief to forestall weld cracking and the Ti-4Al-3Mo-1V exhibited larger reduction in ductility than did Ti-8Al-1Mo-1V.

Preexposure Fatigue Tests

The results of the preexposure fatigue tests are listed in table IV and are presented in figure 5 as S-N curves. The maximum stress in a cycle is plotted against the number of cycles to failure. In all cases except one, the curves displayed a real fatigue limit (a definite tendency to become horizontal before reaching 10^7 cycles). The exception was Ti-6Al-4V in the unnotched configuration (fig. 5(e)) in which case the S-N curve had a negative slope up to 10^7 cycles.

An unusually high degree of scatter was observed in the results for AISI 301 unnotched specimens (fig. 5(d)). Photomicrographs (fig. 6) were taken of this material in a search for possible causes for the scatter. It can be seen that stringer-like inclusions are present and occasionally very large ones are evident up to 0.006 inch (0.015 cm) in size. It is possible that these inclusions may be responsible for early fatigue failures. Such extreme scatter did not occur for the edge-notched and spot-welded specimens probably because the effects of the high stress concentration factor at the notch or weld masked the effects of inclusions.

The fatigue-limit—density ratios of the various materials and types of specimens are compared in figure 7. Densities are given in the appendix. This normalization puts the stainless steels and titanium alloys on a comparable footing since the mean stresses are, fortuitously, in approximately the same ratio as the densities. The results of the tests of unnotched and edge-notched specimens show that the ratios for the stainless steels and titanium alloys are generally equivalent in those configurations. However, in the case of welded joints, both spot-welded and fusion-welded, the titanium alloys had higher ratios. The ratios for currently used aluminum alloys (2024-T3 and 7075-T6) in the edge-notched configuration (ref. 5) are roughly equivalent to those found in this investigation. Figure 7 also shows the ratios for the spot-welded joint to be roughly equivalent to those for the edge-notched specimens.

A measure of the effect of fusion welding on the fatigue limit can be obtained by determining the percent of the fatigue limit for unnotched specimens that was retained by the welded specimens. (See fig. 7.) The percentages for the titanium alloys are higher (83 to 97 percent) than those for the steels (70 to 82 percent). The fatigue limit for Ti-6Al-4V appears to be almost insensitive to fusion welding.

If the materials are serially ranked for each kind of specimen on the basis of fatigue-limit—density ratio S_f/ρ and the rank numbers then added, the results would be a rough overall ranking as has been done in the following table:

Material	Specimen type				Total	Overall rank
	$K_T = 1$	$K_T = 4$	Spot-weld	Fusion-weld		
PH 15-7 Mo	6	2	5	6	19	5
AM 350 CRT	4	5	6	5	20	6
AM 350 DA	2	1	4	4	11	2
AISI 301	7	7	7	7	28	7
Ti-6Al-4V	3	4	3	1	11	2
Ti-4Al-3Mo-1V	5	6	1	3	15	4
Ti-8Al-1Mo-1V	1	3	2	2	8	1

In the ranking of the fusion-welded specimens, those steel specimens which were welded before heat treating were omitted. This ranking should be regarded cautiously since it was drawn from very limited data and from only one type of test.

Postexposure Static Tests

The effect of exposure on the static tensile strength was examined in a cursory manner by use of one standard tensile specimen for each exposure time. A more complete investigation of these effects is reported in reference 6. Table I and figure 8 present the results from the present investigation. No important changes in strength are evident although it may be pointed out that PH 15-7 Mo and AISI 301 showed a consistent rise in tensile ultimate and yield strengths up to 8800 hours.

The results of the static tests of fusion-welded fatigue specimens are given in table V. The only significant change occurred in AM 350 CRT where the strength decreased from 139 ksi to 103 ksi (958 to 710 MN/m^2) in 4400 hours.

Postexposure Fatigue Tests

The results of the fatigue tests of exposed specimens are given in table VI and are plotted in figure 8. The effect of exposure on fatigue life is expressed as a ratio of the as-exposed life to the preexposure life at one particular maximum stress level. The test stress levels were chosen from the faired S-N curves in figure 5 so that preexposure life was between 50,000 and 500,000 cycles. The logarithmic average of the exposure test results was used to compare with the preexposure lives as obtained from the faired S-N curves.

Although the data are somewhat erratic, one important conclusion may be drawn; that is, no catastrophic degradation of fatigue life has been found after exposure to 550° F (561° K). It must be noted, however, that these specimens were not under stress while exposed to elevated temperature. It is known that the addition of stress to a heated material can accelerate metallurgical changes and thereby affect mechanical properties (ref. 7).

The most extreme improvement occurred for the unnotched specimens of Ti-8Al-1Mo-1V. (See fig. 8.) The fatigue-life ratio increased from 1 to 13 in the interval between 4400 hours and 8800 hours. Since half of those specimens tested at 8800 hours failed at normal lifetimes, the sudden rise should probably be ascribed to scatter in the test results, especially since the results for edge-notched specimens did not indicate a similar trend.

A number of points fell at life ratios below 1. However, in most cases, the next exposure interval indicated an increase; thus, the fluctuations could be ascribed to test scatter. But in some cases, such as Ti-4Al-3Mo-1V spot-welded and Ti-8Al-1Mo-1V edge-notched, the life ratio declined steadily up to 8800 hours. Subsequent tests after longer periods of exposure should contribute additional evidence.

CONCLUDING REMARKS

A//

Fatigue and tensile specimens of four stainless steels and three titanium alloys have been exposed to 550° F (561° K) for periods up to 8800 hours. At intervals, the specimens were tested under axial load at room temperature and their fatigue lives and static strengths before and after exposure were determined.

A//

It was found that the preexposure fatigue limits of spot-welded specimens were approximately equal to those of edge-notched specimens with a stress concentration factor of 4. The fatigue limits of fusion-welded specimens were slightly lower than those of unnotched specimens. On the basis of fatigue-limit—density ratios, the stainless steels and titanium alloys were generally equivalent. The titanium alloys, however, had somewhat higher ratios for spot-welded and fusion-welded joints than did the stainless steels.

The efficiencies of spot-welded joints (ratio of strength of joint to that of the virgin sheet material) was substantially higher for titanium alloys than for stainless steels.

The exposure to 550° F (561° K) did not seriously degrade the fatigue life for any of the materials tested during the indicated exposure periods. A slight but steady life-reduction trend was found for Ti-4Al-3Mo-1V spot-welded specimens and Ti-8Al-1Mo-1V edge-notched specimens. The static strengths showed no significant changes due to exposure. end

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 4, 1965.

APPENDIX

FABRICATION AND TREATMENT OF SPECIMENS

Four stainless steel and three titanium alloys were included in this investigation. The chemical composition and densities of these sheet materials obtained from the producers are given in the following tables:

(a) Titanium alloys

Alloy	Chemical composition, percent (on weight basis) (*)									All Density, lb/in.^{3} (g/m^3)
	C	Fe	N_2	H_2	Al	V	Cr	Mo	Ti	
Ti-8Al-1Mo-1V	0.034	0.09	0.013	0.005	7.8	1.1		1.1	Balance	0.156 (4.32)
Ti-6Al-4V	.026	.15	.013	.011	6.1	4.0			Balance	.161 (4.46)
Ti-4Al-3Mo-1V	.015	.16	.011	.010	4.4	1.1		3.0	Balance	.163 (4.51)

*Average for different heats.

(b) Stainless steels

Alloy	Chemical composition, percent (on weight basis)											Density, lb/in.^{3} (g/m^3)
	C	Mn	P	S	Si	Cr	Ni	Co	Mo	Al	Fe	
AM 350	0.080	0.76	0.019	0.012	0.30	16.80	4.15		2.80		Balance	0.286 (7.92)
PH 15-7 Mo	.063	.55	.020	.011	.44	14.96	7.23		2.15	1.14	Balance	.277 (7.67)
AISI 301	.089	.15	.023	.017	.47	17.30	7.70	0.05	.16		Balance	.287 (7.95)

Specimen Fabrication

Unnotched specimens.- The $7\frac{1}{2}$-inch (19-cm) radius of the unnotched specimens (fig. 1) was cut in a lathe by mounting the blanks on the headstock in stacks of 6 to 12 at one time. Machining speed was 14 revolutions per minute or 11 inches (28 cm) per second. Each of the final two passes removed 0.001 inch (25 μm) of material producing a finish of 64 μin. (1.6 μm) root mean square. Although machining techniques were chosen to minimize burrs, they could not be eliminated entirely. Therefore, the corners in the fatigue critical areas were chamfered to remove the burred material. The beveling tool was a block of wood having about a $7\frac{1}{2}$-inch (19-cm) radius with number 600 emery paper fixed to the circumference. The bevel was produced by hand with light longitudinal strokes. The resulting bevel face was approximately 0.004 inch (0.10 mm) wide at a 45° angle to the surface of the specimen.

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Notched specimens.- The notch radii of the notched specimens (fig. 1) were formed by drilling successively larger holes. The final three drill sizes were 0.110 inch, 0.113 inch, and 0.116 inch (2.80, 2.87, and 2.94 mm) diameter. The first two drills were guided by a bushing, but the last drill was free. The blanks were drilled in stacks of 10 against a thick plate of cold-rolled steel. Only new drills were used and each was discarded after drilling the stack once. Drilling speed was 925 revolutions per minute and 11/64 inch per minute (73 μm/s) feed with the drills lubricated continuously. The notches were completed by slotting from the edge with a 3/32-inch (2.38 mm) wide milling tool. Burrs produced by the drilling operation were removed by chamfering the edges of the hole at a 45° angle. The beveling tool was a cone-shaped piece of rubber-abrasive composite chucked in a drill press which ran at 3000 revolutions per minute. The procedure required the specimens to be lightly touched against the cone to produce a chamfer 0.004 inch (0.10 mm) wide.

Spot-welded specimens.- The four components of the spot-welded specimens (fig. 1) were machined to size prior to welding. Edge finish was 64 μin. (1.6 μm) root mean square and the corners were broken with a fine file. Welding parameters and tests were applied to check the weld quality.

Fusion-welded specimens.- The two components of the fusion-welded specimens (fig. 1) were premachined to a rectangular shape. They were then clamped in position in a tungsten inert gas automatic welding machine and welded without filler rod. The radius was machined in the same manner as for the unnotched specimen except that spacers were placed between the fusion-welded specimens away from the weld to compensate for weld bulge while stacked for machining. The weld bulge was left as welded.

Handling and Treatment of Specimens

General requirements.- Sheets were covered with protective paper prior to shearing. Specimens were not scribed, scratched, or marred in anyway. Specimens were separated by paper or racked in designated shipping containers. Handling of specimens was at all times conducive to the retention of a scratch-free and chemically clean surface. The special treatment given each material is outlined in the following table:

Material	Cleaning method	Grit-blast oxidation removal	Heat treatment
PH 15-7 Mo	A	Yes	I
AISI 301	B	No	None
AM 350 CRT	B	No	None
AM 350 DA	B	Yes	II
Ti-6Al-4V	C	No	III
Ti-4Al-3Mo-1V	C	Yes	IV
Ti-8Al-1Mo-1V	C	No	None

APPENDIX

Cleaning methods.- The specimens were cleaned both before heat treatment and immediately before insertion into oven at 550° F (561° K). The three different cleaning processes used are as follows:

Method A:
(1) Remove markings such as manufacturer's stamp, crayon, etc., using acetone or alcohol and cloth.

(2) Vapor degrease using trichlorethylene vapor.

(3) Hand scrub using fiber brush and a detergent.

(4) Hand scrub and rinse in hot running water.

(5) Rinse in cold running water.

(6) Check for uniform wetting of specimen surface.

(7) Wipe dry using clean cloth or paper towels.

Method B:
(1) Remove markings such as manufacturer's stamps, crayon, etc., using acetone or alcohol and cloth.

(2) Vapor degrease using trichlorethylene vapor.

(3) Rinse in hot water.

(4) Immerse in nitric acid, 20 percent by volume, for approximately 5 minutes.

(5) Wash in hot water.

(6) Rinse in cold water.

(7) Check for uniform wetting of specimen surface.

(8) Wipe dry using clean cloth or paper towels.

Method C:
(1) Immerse in alkaline cleaner for 10 minutes. Use at 180° F (355° K) to 200° F (366° K).

(2) Rinse in hot water 2 to 3 minutes.

(3) Immerse in nitric acid, 20 percent by volume, for 30 seconds.

(4) Rinse in hot water, agitated.

(5) Rinse in cold water, agitated, continuous supply.

(6) Check for uniform wetting of specimen surface.

(7) Wipe dry using clean cloth or paper towels.

APPENDIX

Heat treatments.- The procedures used for the heat treatments of the various materials are as follows:

PH 15-7 Mo: Heat treat the material PH 15-7 Mo to the TH 1050 condition as follows:

(1) Heat to 1400° F ± 25° F (1033° K ± 14° K) in argon atmosphere. Hold for 90 minutes.

(2) Cool to 60° F + 0°, -10° F (289° K + 0°, -5° K) within 1 hour. Hold for 30 minutes.

(3) Heat to 1050° F ± 10° F (837° K ± 5° K) in argon atmosphere. Hold for 90 minutes. Air cool to room temperature.

AM 350: Heat treat the material AM 350 to the double-aged condition as follows:

(1) Heat to 1375° F ± 25° F (1022° K ± 14° K) in argon atmosphere. Hold for 3 hours.

(2) Air cool to 80° F + 0°, -10° F (300° K + 0°, -5° K).

(3) Heat to 850° F ± 25° F (727° K ± 14° K) in argon atmosphere. Hold for 3 hours. Air cool to room temperature.

Ti-6Al-4V: Fusion-welded specimens of the material Ti-6Al-4V were stress-relieved within 72 hours after welding as follows:

(1) Heat to 1150° F ± 25° F (894° K ± 14° K) in argon atmosphere for 1 hour.

(2) Air cool to room temperature.

Ti-4Al-3Mo-1V: Heat treat the material Ti-4Al-3Mo-1V as follows:

(1) Heat to 1050° F (837° K) in an argon atmosphere. Hold for 4 hours.

(2) Air cool to room temperature.

Welding procedures.- Prior to welding the spot-weld and fusion-weld components, oxidation was removed by a grit-blast process from the PH 15-7 Mo, AM 350 AM 350 DA, and Ti-4Al-3Mo-1V materials. Prior to welding fatigue specimens, one sample specimen was welded, sectioned, and etched to check penetration and nugget size. Spot-weld shear test qualifying specimens were made according to military specifications MIL-W-6858-B (ref. 8) at the beginning and end of a material run and also after 20 fatigue specimens. A 50 kVA 3ϕ combination seam and spot-welder was used for all spot-welds. It has an electrode face diameter of 5/16 inch (0.67 cm) and a tip radius of 3 inches (7.62 cm). The spot-weld parameters for the various materials are given in the following table:

APPENDIX

Material	Welds per row	Penetration, percent	Nugget diameter, in. (mm)
PH 15-7 Mo	7	70	0.13 (3.3)
AM 350 CRT	7	80	.20 (5.1)
AM 350 DA	7	80	.18 (4.6)
AISI 301	7	75	.16 (4.1)
Ti-6Al-4V	5	80	.24 (6.1)
Ti-4Al-3Mo-1V	5	80	.23 (5.8)
Ti-8Al-1Mo-1V	5	80	.19 (4.8)

The fusion-welds were made without a filler rod. A 200-ampere welding machine was used; its electrode was made of tungsten, 2-percent thoria and had a diameter of 0.040 inch (1.0 mm). The fusion-weld parameters for the various materials are given in the following table:

Material	Shield inert gas flow rate, cu ft/hr			Current, A
	Top (*)	Bottom	Trailing (**)	
PH 15-7 Mo	30	*20	0	19
AM 350 CRT	50	***15	0	24
AM 350 DA	50	***15	0	24
AISI 301	50	***15	0	24
Ti-6Al-4V	30	**5	20	44
Ti-4Al-3Mo-1V	30	**5	30	46
Ti-8Al-1Mo-1V	30	**30	30	42

*75-percent helium, 25-percent argon.
**Argon.
***Helium.

REFERENCES

1. Mechtly, E. A.: The International System of Units - Physical Constants and Conversion Factors. NASA SP-7012, 1964.

2. Spaulding, E. H.: Design for Fatigue, SAE Trans., vol. 62, 1954, pp. 104-116.

3. Randall, M. D.; Monroe, R. E.; and Rieppel, P. J.: Methods of Evaluating Welded Joints. DMIC Rept. 165, Battelle Mem. Inst., Dec. 28, 1961.

4. Grover, H. J.; Hyler, W. S.; Kuhn, Paul; Landers, Charles B.; and Howell, F. M.: Axial-Load Fatigue Properties of 24S-T and 75S-T Aluminum Alloy as Determined in Several Laboratories. NACA Rept. 1190, 1954. (Supersedes NACA TN 2928.)

5. Illg, Walter: Fatigue Tests on Notched and Unnotched Sheet Specimens of 2024-T3 and 7075-T6 Aluminum Alloys and of SAE 4130 Steel With Special Consideration of the Life Range From 2 to 10,000 Cycles. NACA TN 3866, 1956.

6. Heimerl, George J.; Baucom, Robert M.; Manning, Charles R., Jr.; and Braski, David N.: Stability of Four Titanium-Alloy and Four Stainless-Steel Sheet Materials After Exposures up to 22 000 Hours at 550° F (561° K). NASA TN D-2607, 1965.

7. Raring, Richard H.; Freeman, J. W.; Schultz, J. W.; and Voorhees, H. R.: Progress Report of the NASA Special Committee on Materials Research for Supersonic Transports. NASA TN D-1798, 1963.

8. Anon.: Welding: Aluminum, Magnesium Non-Hardening Steels or Alloys, and Titanium, Spot, Seam and Stitch. Mil. Specification MIL-W-6858B, Mar. 22, 1962.

TABLE I.- ROOM-TEMPERATURE TENSILE PROPERTIES FOR TENSILE SPECIMENS, LONGITUDINAL GRAIN DIRECTION

[Each value for 0 exposure time represents four tests. For all other exposure times only one test is represented.]

Material	Exposure time, hr	S_u, ksi	S_u, MN/m^2	S_y, (*) ksi	S_y, (*) MN/m^2	e, percent in 2 in. (5.08 cm)
PH 15-7 Mo TH 1050	0	201	1390	196	1350	7
	2200	205	1420	200	1380	7
	4400	208	1440	202	1390	7
	8800	210	1450	205	1420	7
AM 350 20 percent CRT	0	201	1390	185	1280	19
	2200	192	1330	187	1290	20
	4400	194	1340	189	1310	20
	8800					
AM 350 double aged	0	190	1310	158	1090	13
	2200	192	1330	158	1090	13
	4400	191	1320	157	1080	13
	8800					
AISI 301 50 percent CR	0	216	1500	203	1400	4
	2200	231	1600	199	1380	3
	4400	230	1590	201	1390	3
	8800					
Ti-6Al-4V annealed	0	149	1030	142	983	12
	2200	158	1090	149	1030	11
	4400	159	1100	148	1020	10
	8800					
Ti-4Al-3Mo-1V aged	0	142	983	122	846	10
	2200	142	983	122	846	10
	4400	142	983	122	846	9
	8800	142	983	121	838	10
Ti-8Al-1Mo-1V single annealed	0	157	1080	145	1010	16
	2200	157	1080	144	1000	16
	4400	156	1080	146	1010	17
	8800	157	1080	146	1010	15

*0.2-percent offset.

TABLE II.- ROOM-TEMPERATURE TENSILE PROPERTIES OF FUSION-WELDED SPECIMENS,

GRAIN PARALLEL TO ROLLING DIRECTION

[Four tests per value]

Material	Direction of weld	S_u, ksi (MN/m^2)		S_y, ksi (MN/m^2) (***)		e, percent in 2 in. (5.08 cm)	
		Welded	Virgin	Welded	Virgin	Welded	Virgin
PH 15-7 Mo* TH 1050	Transverse	120 (828)	201 (1390)	105 (724)	196 (1350)	3	7
	Longitudinal	175 (1210)		144 (993)		12	
PH 15-7 Mo** TH 1050	Transverse	197 (1370)	201 (1390)	185 (1280)	196 (1350)	2	7
	Longitudinal	203 (1400)		194 (1340)		10	
AM 350 20 percent CRT	Transverse	132 (910)	201 (1390)	100 (690)	185 (1280)	4	19
	Longitudinal	163 (1120)		106 (731)		9	
AM 350* double aged	Transverse	133 (917)	190 (1310)	103 (710)	158 (1090)	4	13
	Longitudinal	170 (1170)		113 (780)		19	
AM 350** double aged	Transverse	180 (1240)	190 (1310)	150 (1030)	158 (1090)		13
	Longitudinal	178 (1230)		144 (993)			
AISI 301 50 percent CR	Transverse	133 (917)	216 (1500)	70 (483)	203 (1400)	7	4
	Longitudinal	170 (1170)		120 (828)		10	
Ti-6Al-4V annealed	Transverse	150 (1030)	149 (1030)	144 (993)	142 (983)	12	12
	Longitudinal	162 (1120)		157 (1080)		7	
Ti-4Al-3Mo-1V aged	Transverse	143 (986)	142 (983)	125 (862)	122 (846)	8	10
	Longitudinal	156 (1080)		129 (890)		5	
Ti-8Al-1Mo-1V single annealed	Transverse	147 (1010)	157 (1080)	135 (930)	145 (1010)	14	16
	Longitudinal	156 (1080)		106 (731)		10	

*Welded after heat treatment.
**Welded before heat treatment.
***0.2-percent offset.

TABLE III.- ROOM-TEMPERATURE TENSILE STRENGTH OF UNEXPOSED FATIGUE SPECIMENS

[Two tests per value]

Material	S_u, ksi	Tensile strength, ksi (MN/m^2) for -					Percent of S_u for -				
		$K_T = 1$	$K_T = 4$	Spot-weld	Fusion-weld		$K_T = 1$	$K_T = 4$	Spot-weld	Fusion-weld	
					Before heat treatment	After heat treatment				Before heat treatment	After heat treatment
PH 15-7 Mo	201	206 (1420)	214 (1480)	173 (1190)	139 (960)	208 (1440)	102	106	86	69	104
AM 350 CRT	201	195 (1350)	201 (1390)	184 (1270)	139 (960)		97	100	92	69	
AM 350 DA	190	207 (1430)	218 (1500)	169 (1170)	125 (862)	187 (1290)	108	114	89	66	98
AISI 301	216	206 (1420)	198 (1370)	186 (1280)	130 (896)		95	91	86	60	
Ti-6Al-4V	149	152 (1050)	163 (1120)	[a]148 (1020)	160 (1100)		102	109	99	107	
Ti-4Al-3Mo-1V	142	141 (973)	141 (973)	[b]141 (973)	146 (1010)		99	99	99	103	
Ti-8Al-1Mo-1V	157	156 (1080)	167 (1150)	151 (1040)	159 (1100)		99	106	96	101	

[a]Three specimens tested; all three failed away from welds.

[b]One of two specimens tested failed away from welds.

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS

(a) PH 15-7 Mo steel; condition TH 1050

Sheet	S_{max}, ksi	S_{max}, MN/m²	N, kilocycles
K_T = 1; S_{mean} = 40 ksi (276 MN/m²)			
8	160	1104	32
8	160	1104	41
8	160	1104	44
8	140	966	75
8	140	966	84
8	140	966	99
8	140	966	119
8	120	828	73
8	120	828	119
8	120	828	178
8	113	780	158
8	113	780	710
8	113	780	2 873
8	108	745	973
8	108	745	3 516
K_T = 4; S_{mean} = 40 ksi (276 MN/m²)			
8	66.5	459	27
6	65	449	54
4	62	428	41
4	62	428	45
8	62	428	78
2	62	428	94
8	58	400	124
8	58	400	>10 000
8	57	393	>10 000
Spotweld; S_{mean} = 40 ksi (276 MN/m²)			
10	75	518	19
10	75	518	20
10	75	518	21
6	75	518	27
10	55	380	242
10	55	380	250
10	55	380	252
10	50	345	810
10	50	345	2 586
Fusion weld; welded after heat treatment; S_{mean} = 40 ksi (276 MN/m²)			
14	105	725	20
14	105	725	22
14	105	725	33
14	102	704	21
13	102	704	72
14	100	690	36
14	100	690	42
14	100	690	49
14	95	656	44
14	95	656	50
14	95	656	60
14	90	621	24
14	90	621	68
14	90	621	115
Fusion weld, welded after heat treatment; S_{mean} = 40 ksi (276 MN/m²) - Concluded			
14	90	621	120
14	90	621	129
14	90	621	130
14	90	621	170
14	90	621	171
14	90	621	184
14	90	621	328
14	90	621	355
14	87	600	127
14	87	600	215
14	87	600	369
14	85	587	329
14	85	587	1 065
14	82	566	591
14	79	545	2 233
14	79	545	8 140
14	78	538	>10 000
Fusion weld; welded prior to heat treatment; S_{mean} = 40 ksi (276 MN/m²)			
12	115	794	26
12	115	794	32
12	115	794	70
12	110	759	20
12	110	759	57
12	110	759	89
12	110	759	93
12	105	725	47
12	105	725	52
12	105	725	61
12	105	725	261
12	100	690	80
12	100	690	85
12	100	690	97
12	100	690	129
12	100	690	220
12	95	656	275
12	95	656	337
12	95	656	728
12	92	635	206
12	92	635	257
12	92	635	314
12	90	621	58
12	90	621	108
12	90	621	198
12	90	621	223
12	90	621	574
12	90	621	>10 000
12	87	600	843
12	87	600	1 352
12	87	600	>10 000
12	85	587	6 828
12	85	587	>10 000
12	85	587	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(b) AM 350 20 percent CRT steel

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
K_T = 1; S_{mean} = 40 ksi (276 MN/m^2)			
4	160	1104	20
4	160	1104	26
4	160	1104	26
4	155	1070	40
4	155	1070	43
4	155	1070	43
4	150	1035	46
4	150	1035	60
4	150	1035	68
4	140	966	57
4	140	966	80
4	140	966	96
4	130	897	147
4	130	897	170
4	130	897	188
1	125	863	92
1	125	863	220
1	125	863	572
1	125	863	691
4	125	863	1 372
4	120	828	427
1	120	828	587
1	120	828	1 197
1	115	794	272
4	115	794	453
4	115	794	684
4	112	773	211
4	112	773	708
4	112	773	1 019
1	110	759	1 048
4	110	759	>10 000
4	110	759	>10 000
K_T = 4; S_{mean} = 40 ksi (276 MN/m^2)			
4	85	587	11
4	85	587	11
4	85	587	11
4	80	552	16
4	80	552	16
4	80	552	22
4	72	497	23
4	72	497	23
4	72	497	28
4	65	449	38
4	65	449	41
4	65	449	49
4	65	449	53
4	65	449	62
4	60	414	67
4	60	414	67
4	60	414	94
4	58	400	71
1	58	400	87
1	58	400	>10 000
4	57	393	84
1	57	393	1 245
1	57	393	1 792
4	55	380	110
1	55	380	174
4	55	380	1 026
4	55	380	1 862
4	52	359	4 002
1	52	359	>10 000
1	52	359	>10 000

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Spot-weld; S_{mean} = 40 ksi (276 MN/m^2)			
3	75	518	24
3	75	518	26
3	75	518	30
3	75	518	39
3	70	483	43
3	70	483	56
3	65	449	87
3	65	449	88
3	65	449	88
3	65	449	91
3	65	449	98
3	60	414	191
3	60	414	240
3	60	414	249
3	60	414	250
3	55	380	429
3	55	380	510
3	55	380	610
3	55	380	643
3	55	380	844
3	53	366	830
3	53	366	1 296
3	51	352	>300
3	51	352	1 402
3	51	352	1 590
3	49	338	>10 000
3	48	331	9 152
Fusion-weld; S_{mean} = 40 ksi (276 MN/m^2)			
7	115	794	16
7	115	794	17
7	115	794	20
7	110	759	21
7	110	759	32
7	110	759	33
7	105	725	52
7	105	725	59
7	105	725	59
7	100	690	131
7	100	690	141
7	100	690	163
7	100	690	180
7	100	690	204
7	95	656	239
7	95	656	261
7	95	656	677
7	92	635	141
7	92	635	1 764
7	92	635	2 895
7	90	621	379
7	90	621	959
7	90	621	1 315
7	90	621	3 220
7	87	600	243
7	87	600	>10 000
7	87	600	>10 000
7	87	600	>10 000
7	85	587	>10 000
7	85	587	>10 000
7	85	587	>10 000
7	83	572	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(c) AM 350 double-aged steel

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
K_T = 1; S_{mean} = 40 ksi (276 MN/m^2)			
3	160	1104	13
3	160	1104	15
3	160	1104	17
1	150	1035	26
1	150	1035	27
1	150	1035	37
3	140	966	37
1	140	966	37
3	140	966	43
1	140	966	45
3	140	966	74
3	140	966	96
3	140	966	96
1	135	932	116
3	135	932	259
3	130	897	95
3	130	897	170
3	130	897	177
3	130	897	354
3	125	863	565
1	125	863	612
3	125	863	1 398
1	125	863	2 925
1	125	863	>10 000
3	120	828	164
3	120	828	165
1	120	828	>10 000
3	120	828	>10 000
1	115	794	3 571
1	115	794	>10 000
K_T = 4; S_{mean} = 40 ksi (276 MN/m^2)			
3	80	552	9
3	80	552	10
3	80	552	14
3	76	524	14
3	76	524	18
3	76	524	20
3	72	497	20
3	72	497	25
1	72	497	38
1	68	469	22
3	68	469	25
1	68	469	49
K_T = 4; S_{mean} = 40 ksi (276 MN/m^2) Concluded			
3	65	449	47
3	65	449	54
1	65	449	87
3	62	428	71
3	62	428	85
3	62	428	9 141
3	60	414	66
1	60	414	>10 000
1	60	414	>10 000
3	60	414	>10 000
3	52	359	>10 000
3	50	345	>10 000
Spot-weld; S_{mean} = 40 ksi (276 MN/m^2)			
6	75	518	18
6	75	518	24
6	75	518	21
6	70	483	34
6	70	483	38
6	70	483	43
6	70	483	47
6	65	449	71
6	65	449	83
6	65	449	86
6	60	414	111
6	60	414	159
6	60	414	176
6	60	414	231
6	57	393	255
6	57	393	273
6	57	393	289
6	57	393	326
6	55	380	289
6	55	380	330
6	55	380	960
6	55	380	>10 000
6	53	366	5 336
6	52	359	3 489
6	52	359	4 554
6	52	359	8 089
6	51	352	1 942
6	51	352	2 112
6	50	345	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(c) AM 350 double-aged steel - Concluded

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Fusion-weld; welded after heat treatment; S_{mean} = 40 ksi (276 MN/m^2)			
8	125	863	5
8	125	863	8
8	120	828	8
8	120	828	9
8	120	828	11
8	115	794	12
8	115	794	13
8	115	794	25
8	110	759	20
8	110	759	33
8	110	759	47
8	105	725	69
8	105	725	70
8	105	725	71
8	105	725	137
8	100	690	75
8	100	690	154
8	100	690	159
8	100	690	180
8	100	690	188
8	100	690	275
8	97	669	75
8	97	669	246
8	97	669	251
8	97	669	278
8	95	656	136
8	95	656	457
8	95	656	524
8	95	656	550
8	95	656	738
8	92	635	306
8	92	635	383
8	92	635	700
8	90	621	705
8	90	621	994
8	90	621	1 293
8	90	621	1 590
8	90	621	>10 000
8	87	600	1 571
8	87	600	>10 000
8	85	587	1 501
8	85	587	>10 000
8	85	587	>10 000
8	85	587	>10 000
8	80	552	>10 000
8	80	552	>10 000

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Fusion-weld; welded prior to heat treatment; S_{mean} = 40 ksi (276 MN/m^2)			
7	140	966	11
7	140	966	25
7	140	966	26
7	140	966	29
7	130	897	27
7	130	897	30
7	130	897	32
7	130	897	34
7	130	897	35
7	125	863	44
7	125	863	117
7	120	828	45
7	120	828	49
7	120	828	62
7	120	828	89
7	115	794	107
7	115	794	154
7	115	794	202
7	110	759	135
7	110	759	141
7	110	759	238
7	105	725	334
7	105	725	366
7	100	690	151
7	100	690	366
7	100	690	487
7	97	669	787
7	97	669	2 823
7	96	662	624
7	96	662	>10 000
7	92	635	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(d) AISI 301, 50 percent CR steel

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
K_T = 1; S_{mean} = 40 ksi (276 MN/m^2)			
2	140	966	18
2	140	966	21
2	140	966	23
2	140	966	36
2	140	966	37
2	140	966	51
1	130	897	32
2	130	897	33
2	130	897	37
3	122	842	1 741
2	120	828	47
2	120	828	51
2	120	828	63
2	120	828	68
1	120	828	73
2	120	828	81
2	120	828	87
1	120	828	167
1	120	828	425
1	120	828	841
1	120	828	>10 000
1	110	759	72
1	110	759	228
1	110	759	1 964
1	110	759	>8 046
2	110	759	>10 000
2	110	759	>10 000
1	105	725	3 693
1	100	690	75
1	100	690	106
2	100	690	176
1	100	690	210
2	100	690	1 720
2	100	690	6 770
1	100	690	>10 000
K_T = 4; S_{mean} = 40 ksi (276 MN/m^2)			
2	70	483	17
2	70	483	18
2	70	483	21
2	65	449	20
1	65	449	28
1	65	449	30
2	60	414	43
2	60	414	52
2	60	414	59
1	60	414	>10 000
2	57	393	62
1	57	393	103
1	57	393	7 529
2	57	393	>10 000
1	57	393	>10 000
1	57	393	>10 000
1	55	380	94
2	55	380	108
2	55	380	271
2	55	380	425
2	55	380	9 879
1	52	359	506
2	52	359	630
1	52	359	5 265
1	52	359	>10 000
2	50	345	2 018
2	50	345	7 904
1	50	345	>10 000
1	48	331	>10 000
2	48	331	>10 000
2	48	331	>10 000

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Spot-weld; S_{mean} = 40 ksi (276 MN/m^2)			
7	70	483	18
7	70	483	19
7	70	483	19
7	65	449	30
7	65	449	32
7	65	449	36
7	65	449	54
7	60	414	71
7	60	414	71
7	60	414	76
7	60	414	125
7	57	393	110
7	57	393	126
7	57	393	145
7	55	380	137
7	55	380	167
7	55	380	186
7	55	380	332
7	53	366	256
7	53	366	257
7	53	366	294
7	52	359	290
7	52	359	387
7	52	359	437
7	52	359	>10 000
7	51	352	387
7	51	352	422
7	51	352	608
7	50	345	695
7	50	345	777
7	48	331	>10 000
7	48	331	>10 000
Fusion-weld; S_{mean} = 40 ksi (276 MN/m^2)			
6	87	600	61
6	87	600	66
6	87	600	115
6	85	587	39
6	85	587	48
6	85	587	103
6	83	573	309
6	83	573	312
6	83	573	573
6	82	566	86
6	82	566	108
6	82	566	9 991
6	82	566	>10 000
6	80	532	114
6	80	532	198
6	80	532	>10 000
6	80	532	>10 000
6	78	538	>10 000
6	78	538	>10 000
6	75	518	>10 000
6	75	518	>10 000
6	75	518	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(e) Ti-6Al-4V annealed titanium

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
K_T = 1; S_{mean} = 25 ksi (173 MN/m^2)			
1	120	828	16
1	120	828	22
2	120	828	28
2	110	759	14
2	110	759	52
2	110	759	54
1	100	690	46
2	100	690	94
2	100	690	145
1	96	662	117
2	95	656	78
2	95	656	113
2	95	656	321
2	95	656	691
2	90	621	615
2	90	621	902
2	85	587	62
1	85	587	544
2	85	587	600
2	85	587	847
2	85	587	1 058
2	80	552	342
2	80	552	901
1	80	552	1 925
1	80	552	2 116
1	80	552	2 512
1	76	524	2 091
1	76	524	2 176
1	76	524	3 087
1	72	497	2 910
2	72	497	6 526
1	72	497	9 081
1	70	483	2 648
1	70	483	2 695
1	68	469	4 345
1	68	469	5 360
1	68	469	7 049
K_T = 4; S_{mean} = 25 ksi (173 MN/m^2)			
1	60	414	7
1	55	380	12
1	55	380	12
2	55	380	16
1	50	345	17
1	50	345	21
1	50	345	26
1	45	311	13
1	45	311	24
1	45	311	31
2	40	276	57
1	40	276	57
1	40	276	112
1	40	276	152
2	40	276	315
2	38	262	54
2	38	262	59
1	37	255	83
1	37	255	3 409
1	36	248	60
2	36	248	85
2	36	248	1 870
2	35	242	76
2	35	242	>10 000
2	34	235	1 846
2	34	235	2 105
2	34	235	2 704
2	34	235	>10 000
2	33	228	206
2	33	228	8 448
2	33	228	>8 075
2	32	221	>10 000
2	32	221	>10 000

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Spot-weld; S_{mean} = 25 ksi (173 MN/m^2)			
7	48	331	21
7	48	331	28
7	48	331	28
7	45	311	32
7	45	311	35
7	45	311	51
7	45	311	58
7	42	290	55
7	40	276	49
7	40	276	72
7	40	276	86
7	40	276	132
7	40	276	133
7	38	262	222
7	37	255	99
7	37	255	124
7	37	255	175
7	37	255	178
7	35	242	334
7	35	242	415
7	35	242	592
7	34	235	>10 000
7	34	235	>10 000
7	33	228	>10 000
7	33	228	>10 000
7	30	207	>10 000
7	30	207	>10 000
7	30	207	>10 000
Fusion-weld; S_{mean} = 25 ksi (173 MN/m^2)			
3	90	621	19
3	90	621	24
3	90	621	32
3	85	587	18
3	85	587	22
3	85	587	23
3	80	552	26
3	80	552	36
3	80	552	66
3	75	518	55
3	75	518	80
3	75	518	98
3	70	483	41
3	70	483	58
3	70	483	107
3	70	483	277
3	70	483	537
3	68	469	503
3	68	469	1 453
3	68	469	3 293
3	65	449	112
3	65	449	1 026
3	65	449	7 327
3	65	449	>10 000
3	63	435	404
3	63	435	1 061

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(f) Ti-4Al-3Mo-1V aged titanium

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
$K_T = 1$; $S_{mean} = 25$ ksi (173 MN/m^2)			
1	110	759	11
1	110	759	14
1	110	759	15
1	100	690	14
1	100	690	16
1	100	690	21
1	90	621	17
1	90	621	19
1	90	621	29
1	84	580	28
1	84	580	41
1	82	566	34
1	82	566	56
1	82	566	78
1	80	552	49
1	75	518	41
2	75	518	65
1	75	518	67
2	70	483	69
2	70	483	80
2	70	483	178
1	70	483	200
1	68	469	126
1	68	469	193
1	68	469	316
1	68	469	>10 000
1	66	455	201
1	66	455	213
1	66	455	>10 000
2	65	449	>10 000
1	63	435	>10 000
1	60	414	>10 000
$K_T = 4$; $S_{mean} = 25$ ksi (173 MN/m^2)			
2	45	311	10
2	42	290	13
2	42	290	13
2	42	290	16
2	40	276	18
1	40	276	19
2	40	276	23
2	37	255	28
2	37	255	31
2	37	255	32
2	35	242	44
2	35	242	51
2	35	242	63
2	33	228	79
2	33	228	82
1	33	228	145
2	32	221	182
2	32	221	199
2	32	221	201
1	32	221	>10 000
2	32	221	>10 000
2	31	214	476
2	31	214	>10 000
2	31	214	>10 000
2	31	214	>10 000

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
Spot-weld; $S_{mean} = 25$ ksi (173 MN/m^2)			
3	48	331	27
3	48	331	31
5	48	331	36
5	45	311	34
5	45	311	40
3	45	311	49
3	45	311	51
3	42	290	70
3	42	290	82
3	42	290	97
5	40	276	84
5	40	276	108
5	40	276	155
5	40	276	167
5	40	276	222
3	38	262	181
5	38	262	>10 000
5	38	262	>10 000
3	38	262	>10 000
3	38	262	>10 000
5	38	262	>10 000
5	35	242	>10 000
5	35	242	>10 000
Fusion-weld; $S_{mean} = 25$ ksi (173 MN/m^2)			
6	75	518	16
6	75	518	17
6	75	518	19
5	70	483	26
5	70	483	30
5	70	483	39
6	65	449	27
6	65	449	29
5	65	449	56
6	62	428	32
6	62	428	36
6	62	428	91
6	62	428	169
5	60	414	47
6	60	414	78
6	60	414	80
6	60	414	>10 000
6	58	400	48
6	58	400	73
5	55	380	61
5	55	380	66
5	55	380	>10 000
6	53	366	2 032
5	53	366	>10 000
6	53	366	>10 000
5	50	345	>10 000
6	50	345	>10 000

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Concluded

(g) Ti-8Al-1Mo-1V annealed titanium

Sheet	S_{max}, ksi	S_{max}, MN/m^2	N, kilocycles
K_T = 1; S_{mean} = 25 ksi (173 MN/m^2)			
8	110	759	21
8	110	759	22
8	110	759	28
8	100	690	19
8	100	690	23
8	100	690	57
8	95	656	24
8	95	656	27
8	95	656	45
8	95	656	64
8	90	621	38
8	90	621	59
8	90	621	80
8	90	621	89
8	90	621	127
8	85	587	46
8	85	587	71
8	85	587	97
8	85	587	979
8	85	587	1 365
8	85	587	9 420
8	80	552	122
8	80	552	124
8	80	552	138
8	80	552	505
8	80	552	1 471
8	80	552	1 522
8	77	531	2 960
8	77	531	4 435
8	75	518	262
8	75	518	319
8	75	518	2 804
8	72	497	3 275
8	72	497	>10 000
8	72	497	1 840
8	70	483	7 921
8	70	483	9 955
8	70	483	1 595
8	70	483	>10 000
8	70	483	>10 000
8	66	455	>10 000
8	66	455	>10 000
8	66	455	>10 000
K_T = 4; S_{mean} = 25 ksi (173 MN/m^2)			
7	50	345	15
7	50	345	19
7	50	345	26
7	47	324	15
7	47	324	20
7	47	324	21
7	45	311	24
7	45	311	58
7	45	311	221
7	43	297	24
7	43	297	71
7	43	297	444
7	42	290	75
7	42	290	562
7	40	276	429
7	40	276	453
7	40	276	459
7	40	276	635
7	40	276	642
7	37	255	110
7	37	255	569
7	37	255	695
7	35	242	1 167
7	35	242	1 691
7	33	228	733
7	33	228	1 651
7	33	228	1 796
7	32	221	3 571
7	32	221	9 252
7	32	221	>10 000
7	30	207	>10 000
7	30	207	>10 000
7	30	207	>10 000
Spot-weld; S_{mean} = 25 ksi (173 MN/m^2)			
3	48	331	24
3	48	331	25
3	48	331	32
3	48	331	81
3	45	311	32
3	45	311	58
3	45	311	80
3	45	311	109
6	43	297	46
6	43	297	47
6	43	297	57
6	43	297	97
3	43	297	139
3	40	276	73
3	40	276	105
3	40	276	226
6	38	262	107
3	38	262	155
3	38	262	196
3	36	248	351
3	36	248	439
6	35	242	185
3	35	242	289
3	35	242	432
3	35	242	659
3	34	235	7 987
3	34	235	8 864
6	34	235	>10 000
6	33	228	593
6	33	228	>10 000
Fusion-weld; S_{mean} = 25 ksi (173 MN/m^2)			
5	90	621	25
5	90	621	26
5	90	621	27
5	85	587	24
5	85	587	32
5	85	587	33
5	80	552	28
5	80	552	29
5	80	552	38
5	78	538	55
5	78	538	80
5	76	524	31
5	76	524	104
5	76	524	1 374
5	75	518	49
5	75	518	74
5	75	518	96
5	75	518	173
5	74	511	262
5	72	497	54
5	72	497	62
5	72	497	75
5	72	497	620
5	70	483	664
5	70	483	893
5	70	483	2 212
5	68	469	91
5	68	469	1 693
5	68	469	2 801
5	65	449	1 932
5	64	442	548
5	64	442	1 905
5	64	442	5 760
5	62	428	2 896
5	62	428	5 066
5	62	428	5 985
5	62	428	6 588
5	60	414	4 227
5	60	414	5 365
5	60	414	>10 000
5	58	400	4 943
5	58	400	5 615
5	58	400	8 599

TABLE V.- STATIC STRENGTH OF FUSION-WELDED FATIGUE

SPECIMENS AFTER EXPOSURE TO 550° F (561° K)

[One specimen per period]

Material	S_u, ksi, after exposure to 550° F (561° K) for -		
	0 hr	2200 hr	4400 hr
PH 15-7 Mo*	139	140	148
PH 15-7 Mo**	208	205	208
AM 350 CRT	139	132	103
AM 350 DA*	125	131	131
AM 350 DA**	187	182	184
AISI 301	130	122	123
Ti-6Al-4V	160	162	163
Ti-4Al-3Mo-1V	146	148	150
Ti-8Al-1Mo-1V	159	160	163

*Welded after heat treatment.
**Welded before heat treatment.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS

[Specimens which did not fail were excluded from calculation of geometric mean]

(a) PH 15-7 Mo; S_{mean} = 40 ksi (276 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 113 ksi (780 MN/m^2)						
400	3 3 3 3 3	240 338 348 459 787 400*	7 7 7 7 7	106 159 208 258 310 195*	7 7 7 7 7	261 825 908 1 203 1 322 792*
K_T = 4; S_{max} = 62 ksi (428 MN/m^2)						
70	6 6 6 6 6	47 49 66 67 69 59*	6 6 6 6 6	36 45 47 58 155 59*	7 7 7 7 7	43 46 54 54 74 53*
Spotweld; S_{max} = 67 ksi (462 MN/m^2)						
50	10 10 10 10 10	46 48 51 64 72 55*	10 10 10 10 10	59 59 68 69 98 71*	10 10 10 10 10	74 79 101 107 111 94*
Fusion-weld (welded after heat treatment); S_{max} = 90 ksi (621 MN/m^2)						
150	14 14 14 14 14	173 174 196 239 260 205*				
Fusion-weld (welded before heat treatment); S_{max} = 100 ksi (690 MN/m^2)						
	12 12 12 12 12	74 86 90 100 180 100*	12 12 12 12 12	54 58 63 133 263 93*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(b) AM 350 (20 percent CRT); S_{mean} = 40 ksi (276 MN/m²)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 130 ksi (897 MN/m²)						
170	1	42	1	93	1	53
	1	71	1	126	1	117
	4	149	1	261	1	139
	4	229	4	278	4	200
	1	286	4	364		
		124*		198*		115*
K_T = 4; S_{max} = 65 ksi (449 MN/m²)						
40	4	38	1	36	1	32
	4	41	1	43	4	37
	1	44	1	45	1	38
	1	48	1	50	4	39
	1	7 690	1	6 629	4	43
		43*		43*		38*
Spotweld; S_{max} = 55 ksi (380 MN/m²)						
500	3	579	3	687	3	620
	3	652	3	803	3	690
	3	695	3	884	3	817
	3	1 233	3	1 312	3	1 161
	3	1 795	3	1 547	3	1 666
		945*		1 002*		1 000*
Fusion-weld; S_{max} = 100 ksi (690 MN/m²)						
140	7	72	7	65		
	7	90	7	69		
	7	111	7	85		
	7	118	7	87		
	7	155	7	90		
		106*		83*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(c) AM 350 (double aged); S_{mean} = 40 ksi (276 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 140 ksi (966 MN/m^2)						
60	1	54	3	52	1	28
	3	61	3	55	3	46
	3	78	3	56	1	61
	3	98	1	57	1	67
	3	102	3	80	3	89
		76*		60*		54*
K_T = 4; S_{max} = 65 ksi (449 MN/m^2)						
50	1	22	3	35	3	22
	3	33	3	36	3	25
	3	39	3	38	3	26
	1	63	3	50	3	30
	3	132	1	88	1	33
		47*		55*		26*
Spot-weld; S_{max} = 57 ksi (393 MN/m^2)						
300	6	227	6	217	6	249
	6	263	6	262	6	298
	6	306	6	277	6	329
	6	322	6	329	6	339
			6	392	6	375
		277*		295*		315*
Fusion-weld (welded after heat treatment); S_{max} = 100 ksi (690 MN/m^2)						
130	8	40	8	30		
	8	49	8	36		
	8	64	8	43		
	8	81	8	47		
	8	117	8	55		
		65*		41*		
Fusion-weld (welded before heat treatment); S_{max} = 115 ksi (794 MN/m^2)						
120	7	81	7	61		
	7	96	7	72		
	7	116	7	85		
	7	196	7	125		
	7	228	7	129		
		143*		90*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(d) AISI 301 (50 percent CR); S_{mean} = 40 ksi (276 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 120 ksi (828 MN/m^2)						
80	2 2 1 1 1	114 282 >8 853 >12 600 >14 540 660*	2 2 1 1	113 114 201 >10 650 139*	2 2 1 2 1	50 55 71 113 >10 200 58*
K_T = 4; S_{max} = 60 ksi (414 MN/m^2)						
55	1 2 1 1 2	37 38 48 66 >15 000 46*	1 1 1 2 2	34 52 62 >10 230 >10 446 48*	1 1 2 1 2	38 46 53 2 036 6 828 264*
Spot-weld; S_{max} = 57 ksi (393 MN/m^2)						
120	7 7 7 7 7	115 120 126 128 129 123*	7 7 7 7 7	106 125 134 135 155 131*	7 7 7 7 7	108 113 125 130 134 123*
Fusion-weld; S_{max} = 82 ksi (566 MN/m^2)						
300	6 6 6 6	61 93 129 143 101*	6 6 6 6 6	68 92 115 134 141 106*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(e) Ti-6Al-4V; S_{mean} = 25 ksi (173 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 100 ksi (690 MN/m^2)						
130	2	78	2	73	2	68
	1	91	2	89	2	79
	1	105	1	128	1	240
	2	132	1	182	1	1 110
	1	534	1	1 119		
		139*		176*		194*
K_T = 4; S_{max} = 40 ksi (276 MN/m^2)						
50	2	33	1	33	1	36
	1	35	1	38	1	36
	2	41	2	40	2	47
	1	50	1	45	2	48
	1	51	2	1 255	1	67
		41*		78*		46*
Spot-weld; S_{max} = 40 ksi (276 MN/m^2)						
90	7	127	7	155	7	88
	7	165	7	160	7	123
	7	167	7	220	7	125
	7	189	7	225	7	157
	7	229	7	261	7	189
		172*		187*		134*
Fusion-weld; S_{max} = 75 ksi (518 MN/m^2)						
70	3	53	3	43		
	3	56	3	51		
	3	83	3	53		
	3	89	3	107		
	3	133	3	228		
		78*		78*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(f) Ti-4Al-3Mo-1V; S_{mean} = 25 ksi (173 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 70 ksi (483 MN/m^2)						
120	1 1 1	42 119 246 107*	1 1 1 1 1	70 202 >10 072 >12 715 >14 643 120*	2 2 2 2 2	120 141 194 >10 414 >15 092 147*
K_T = 4; S_{max} = 33 ksi (228 MN/m^2)						
100	2 2 2 2 2	69 74 89 92 104 85*	2 2 2 2 2	67 92 110 186 563 148*	1 1 1 1 1	112 117 530 >10 000 >12 800 191*
Spot-weld; S_{max} = 40 ksi (276 MN/m^2)						
120	5 5 3 3 3	82 90 97 116 133 103*	5 3 3 3 3	60 75 85 103 103 83*	5 5 5 3 3	52 59 61 62 74 61*
Fusion-weld; S_{max} = 62 ksi (428 MN/m^2)						
50	6 6 5 6 5	40 41 43 50 52 45*	5 6 6 6 5	30 34 56 65 75 51*		

*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Concluded

(g) Ti-8Al-1Mo-1V; S_{mean} = 25 ksi (173 MN/m^2)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
N_i, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
K_T = 1; S_{max} = 90 ksi (621 MN/m^2)						
70	8 8 8 8 8	49 78 90 92 361 103*	8 8 8 8 8	59 60 94 151 216 102*	8 8 8 8	86 155 1 268 4 401 933*
K_T = 4; S_{max} = 40 ksi (276 MN/m^2)						
200	7 7 7 7 7	44 46 48 48 56 48*	7 7 7 7 7	33 40 59 493 59 74*	7 7 7 7 7	35 35 56 60 43 45*
Spot-weld; S_{max} = 38 ksi (262 MN/m^2)						
200	6 3 6 3 3	121 141 186 290 575 221*	3 6 3 3 6	139 153 204 208 217 181*	6 6 3 3 3	140 168 419 503 559 314*
Fusion-weld; S_{max} = 75 ksi (518 MN/m^2)						
100	5 5 5 5 5	42 67 89 156 323 135*	5 5 5 5 5	47 74 115 116 156 113*		

*Geometric mean.

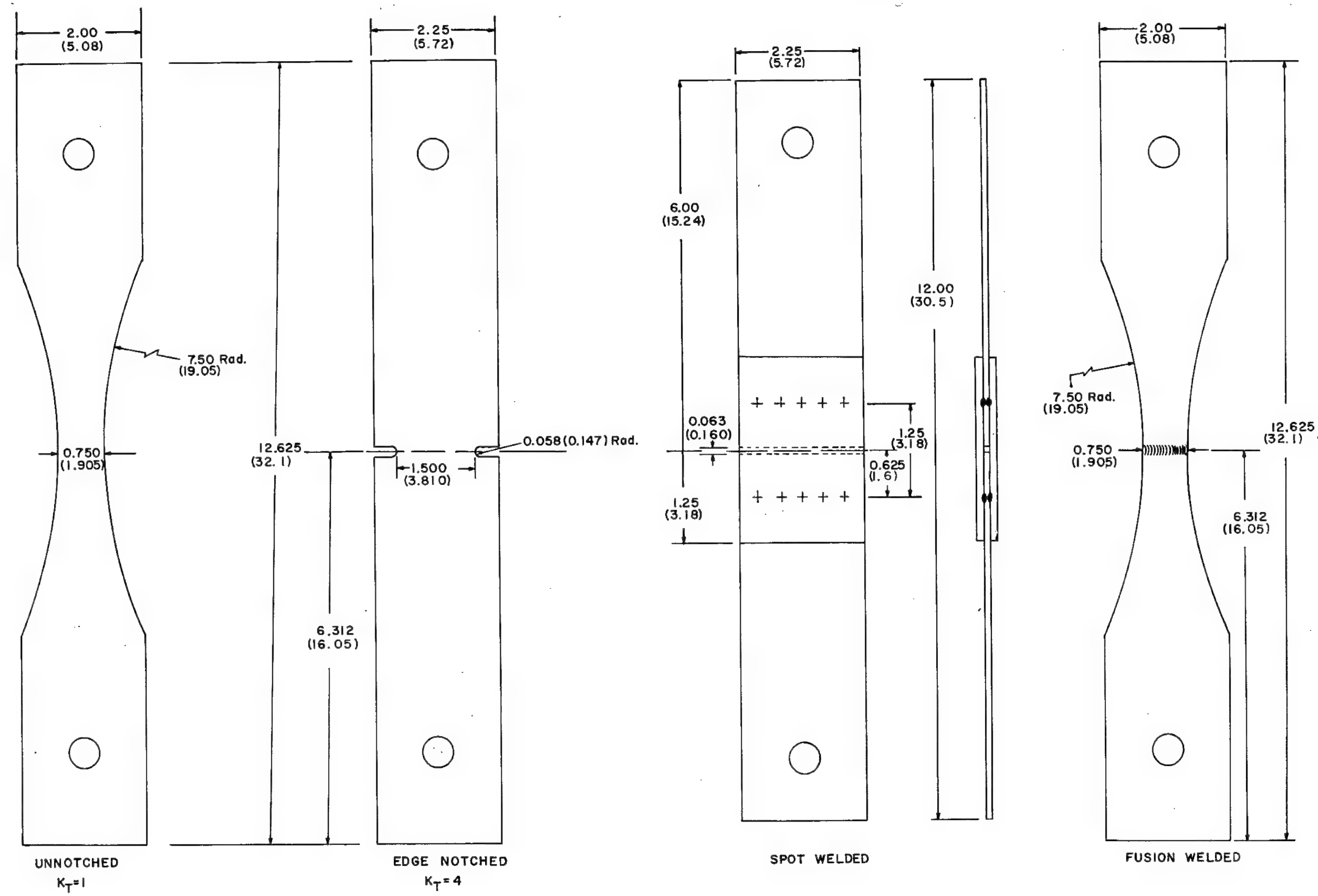

Figure 1.- Fatigue specimens. All dimensions are in inches (centimeters).

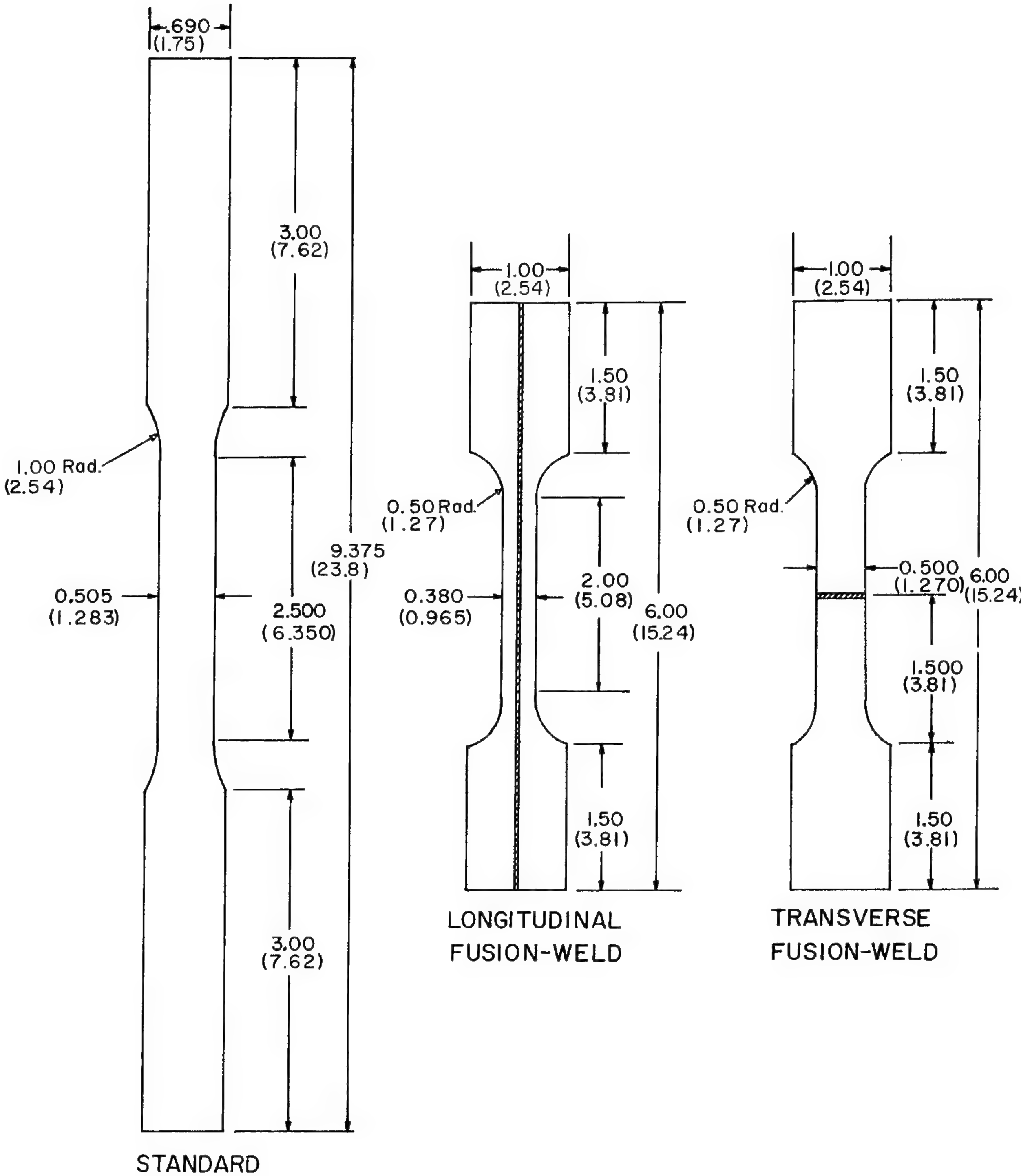

Figure 2.- Tensile specimens. All dimensions are in inches (centimeters).

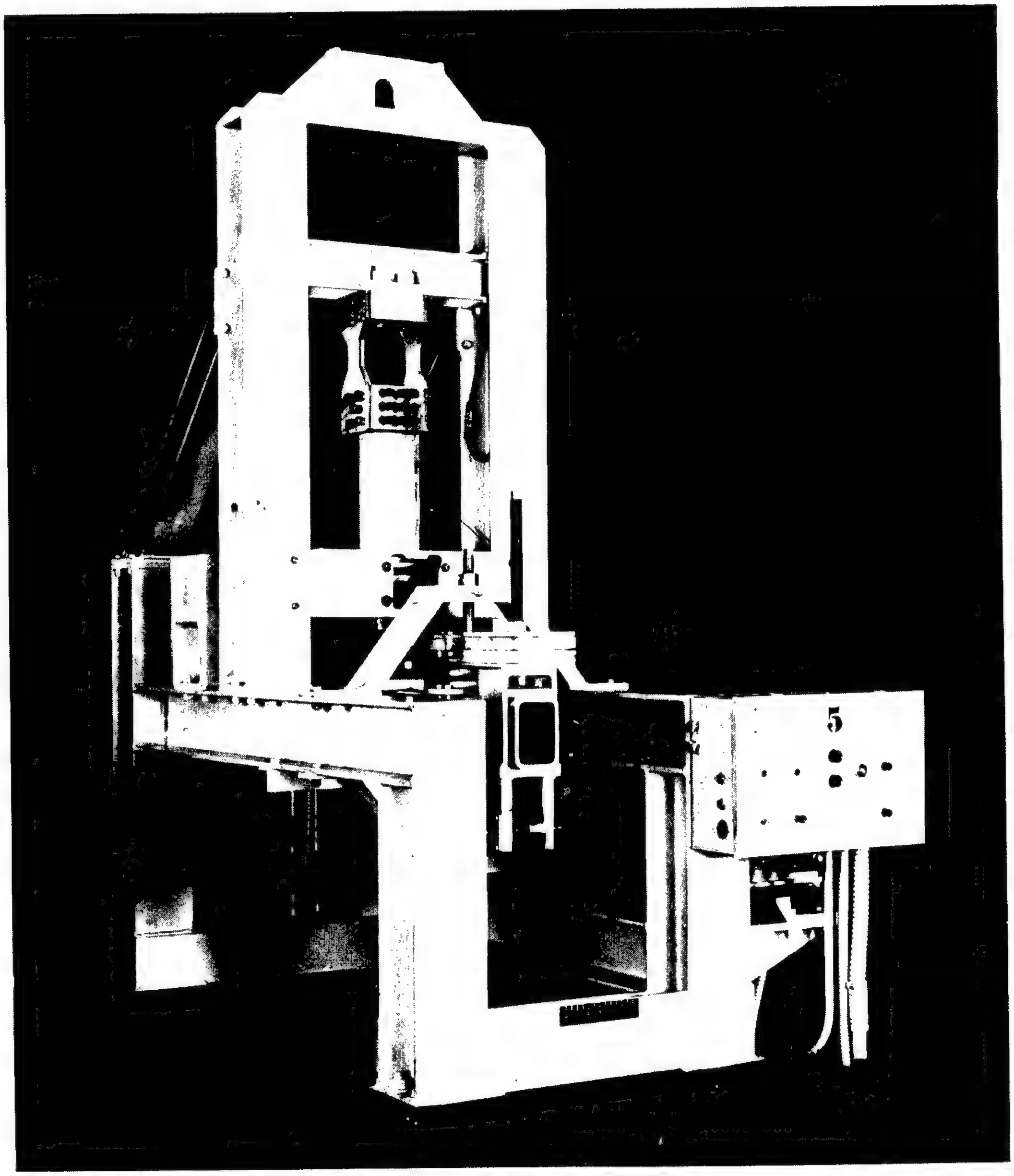

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Figure 3.- Subresonant axial-load fatigue testing machine.

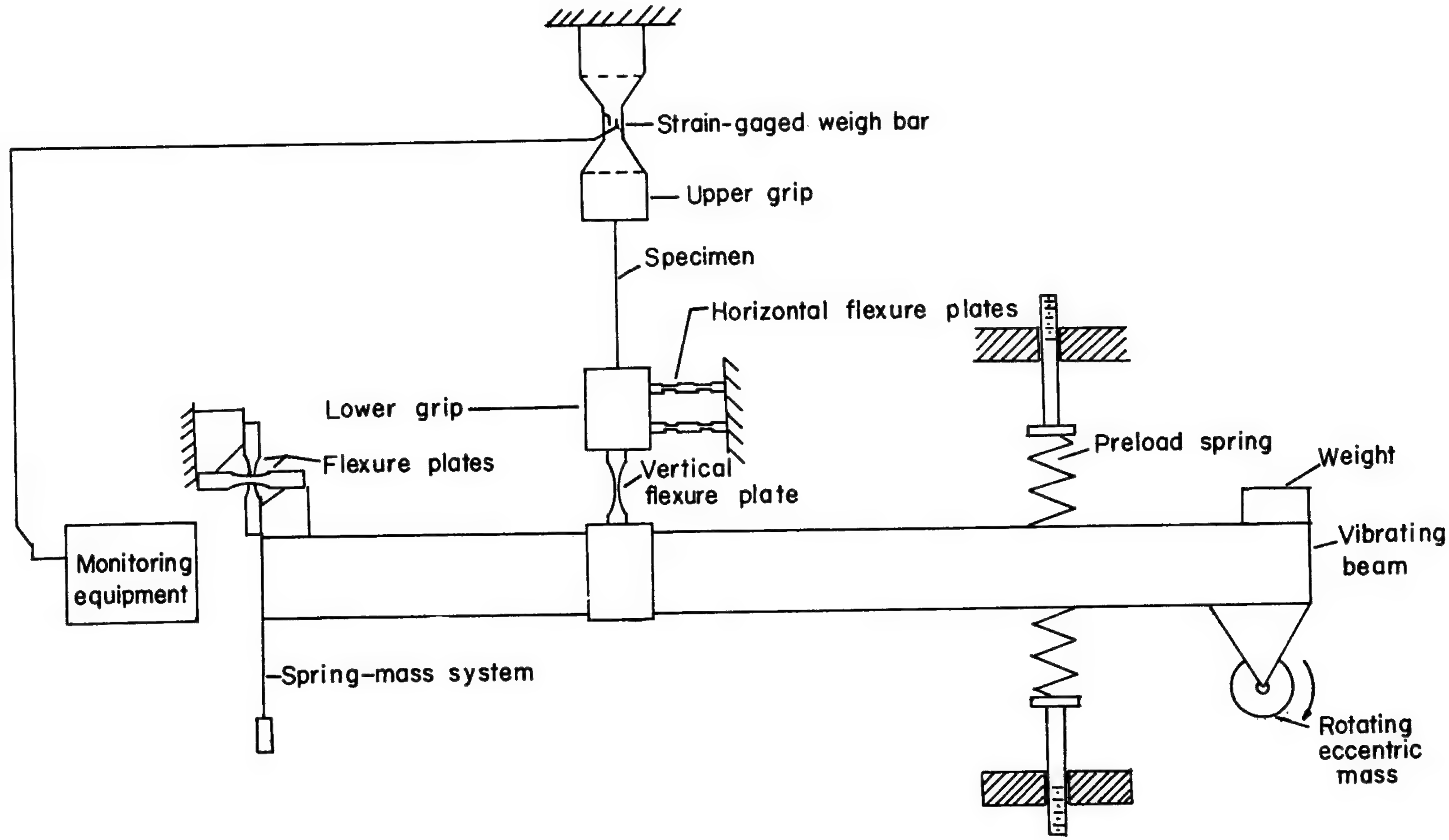
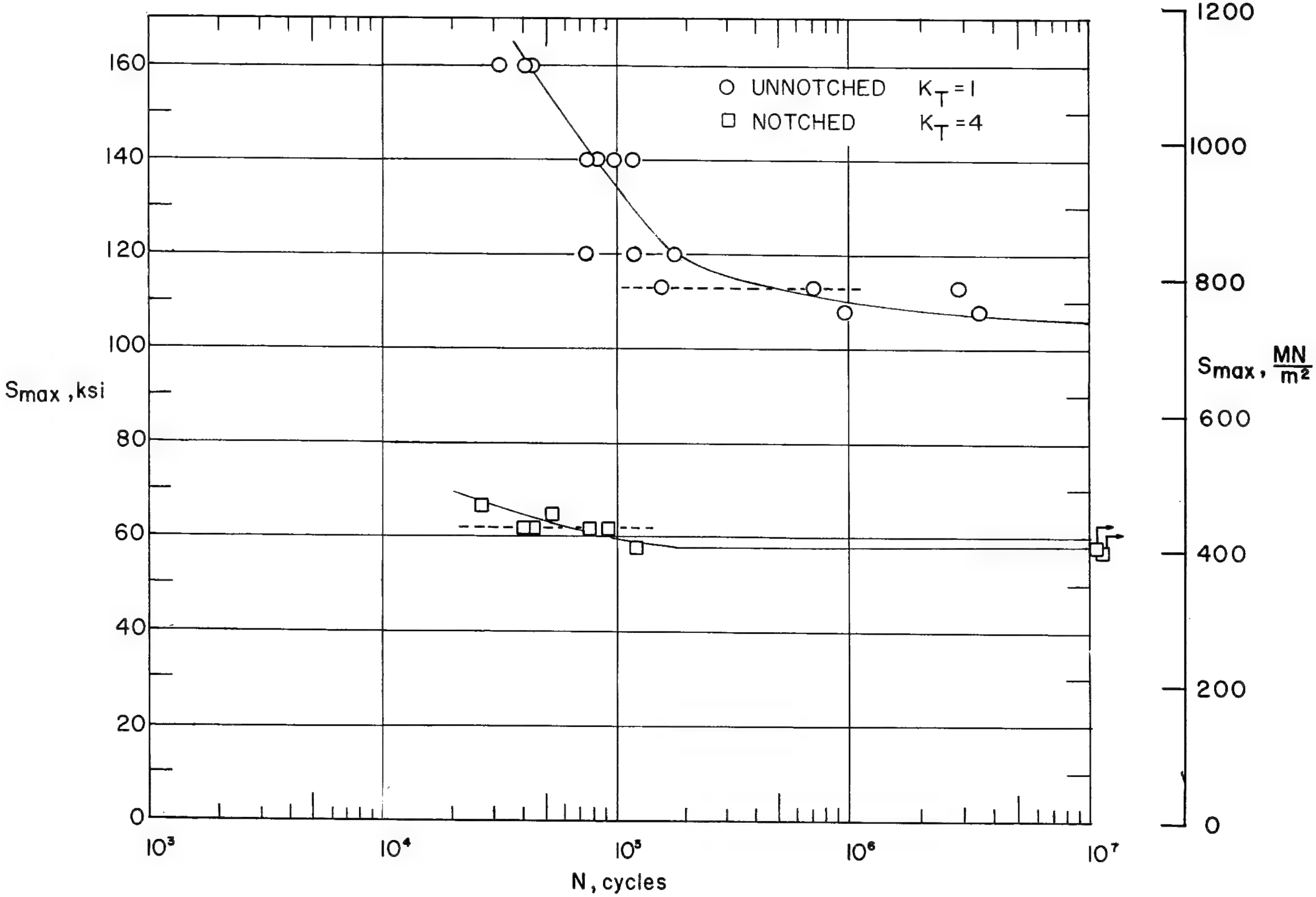
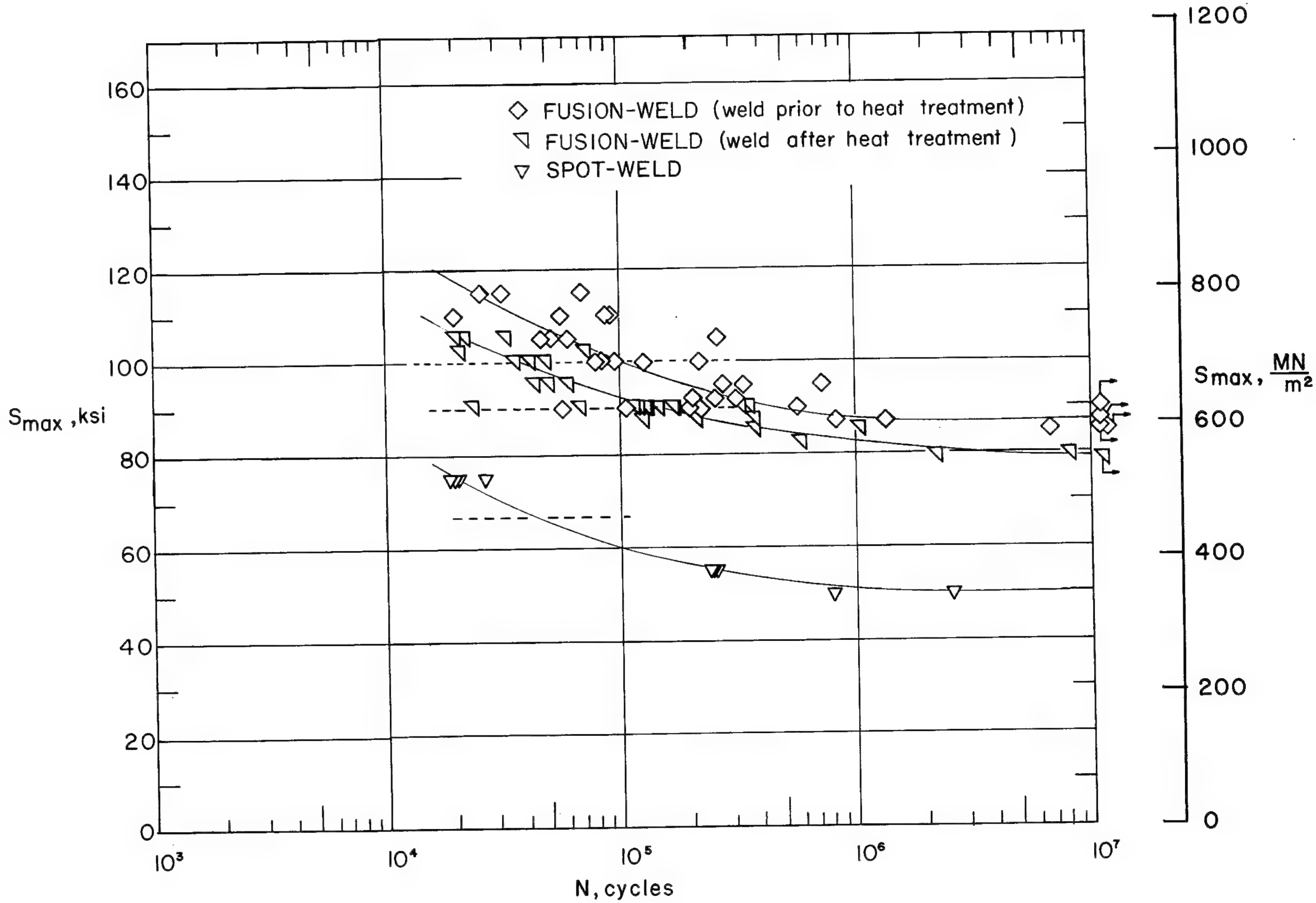


Figure 4.- Schematic of subresonant axial-load fatigue testing machine.



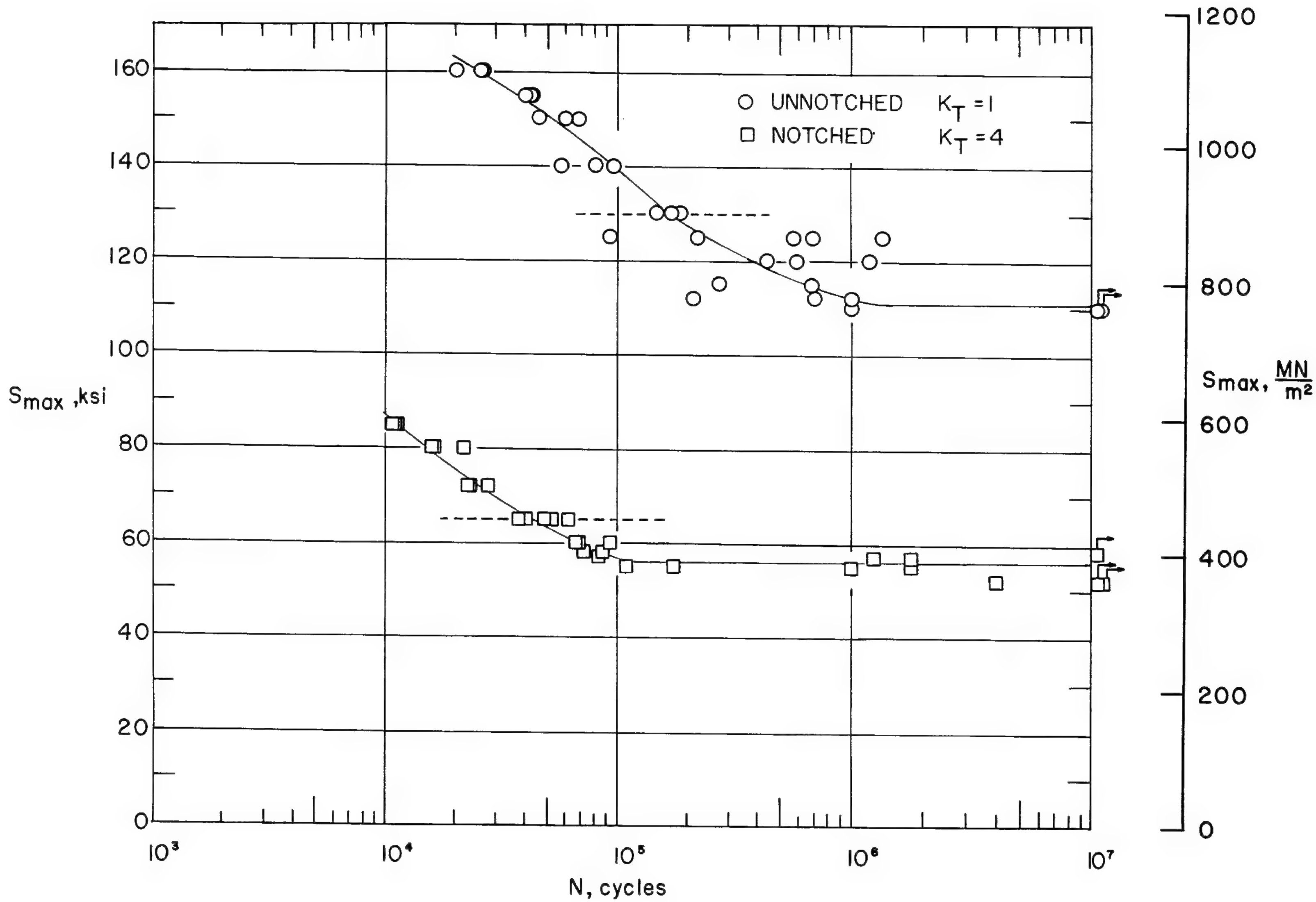
(a) PH 15-7Mo, condition TH 1050; mean stress, 40 000 psi (276 MN/m^2).

Figure 5.- Results of axial-load tests. Dashed line represents postexposure stress level.



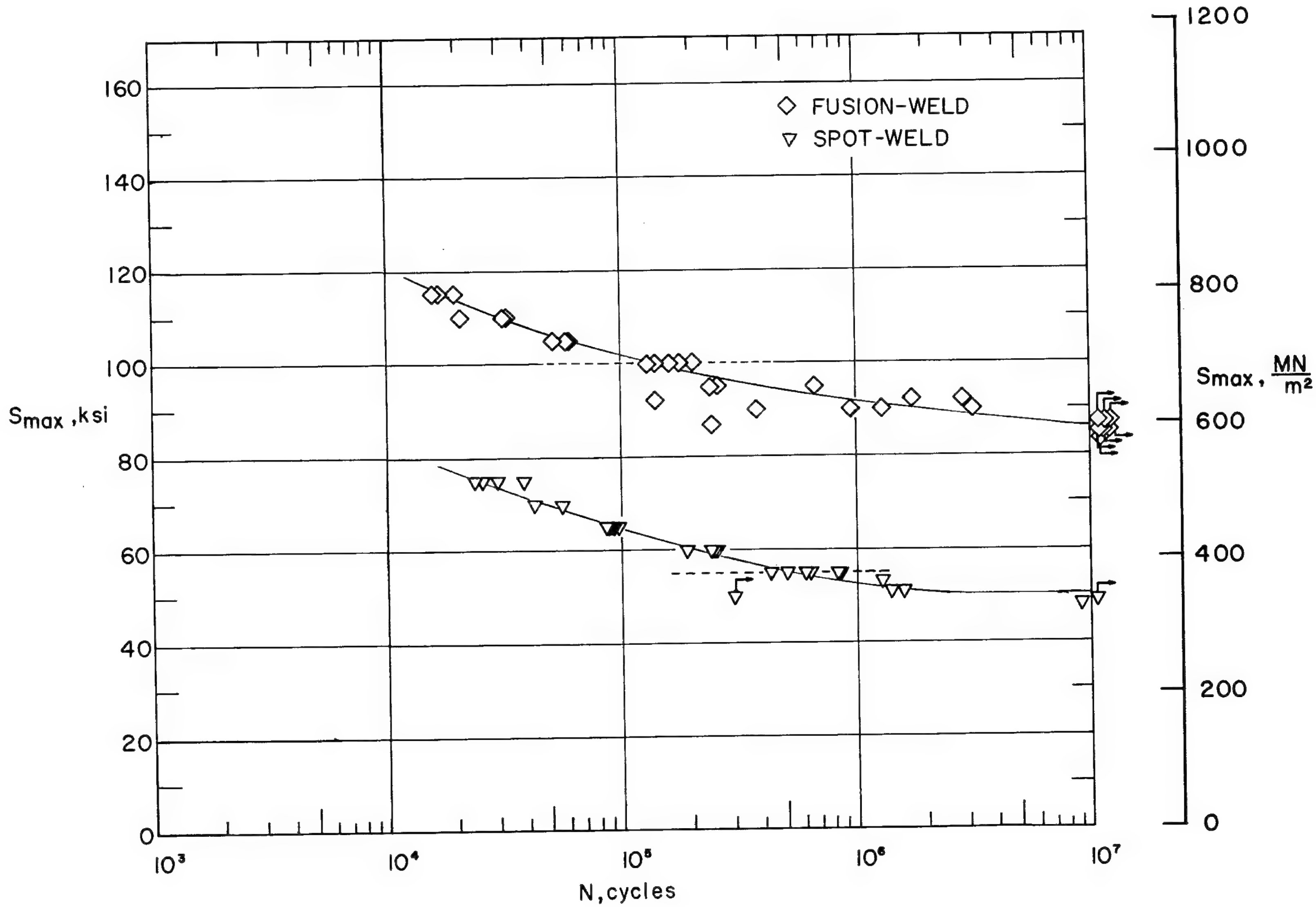
(a) PH 15-7Mo, condition TH 1050; mean stress, 40 000 psi (276 MN/m^2). Concluded.

Figure 5.- Continued.



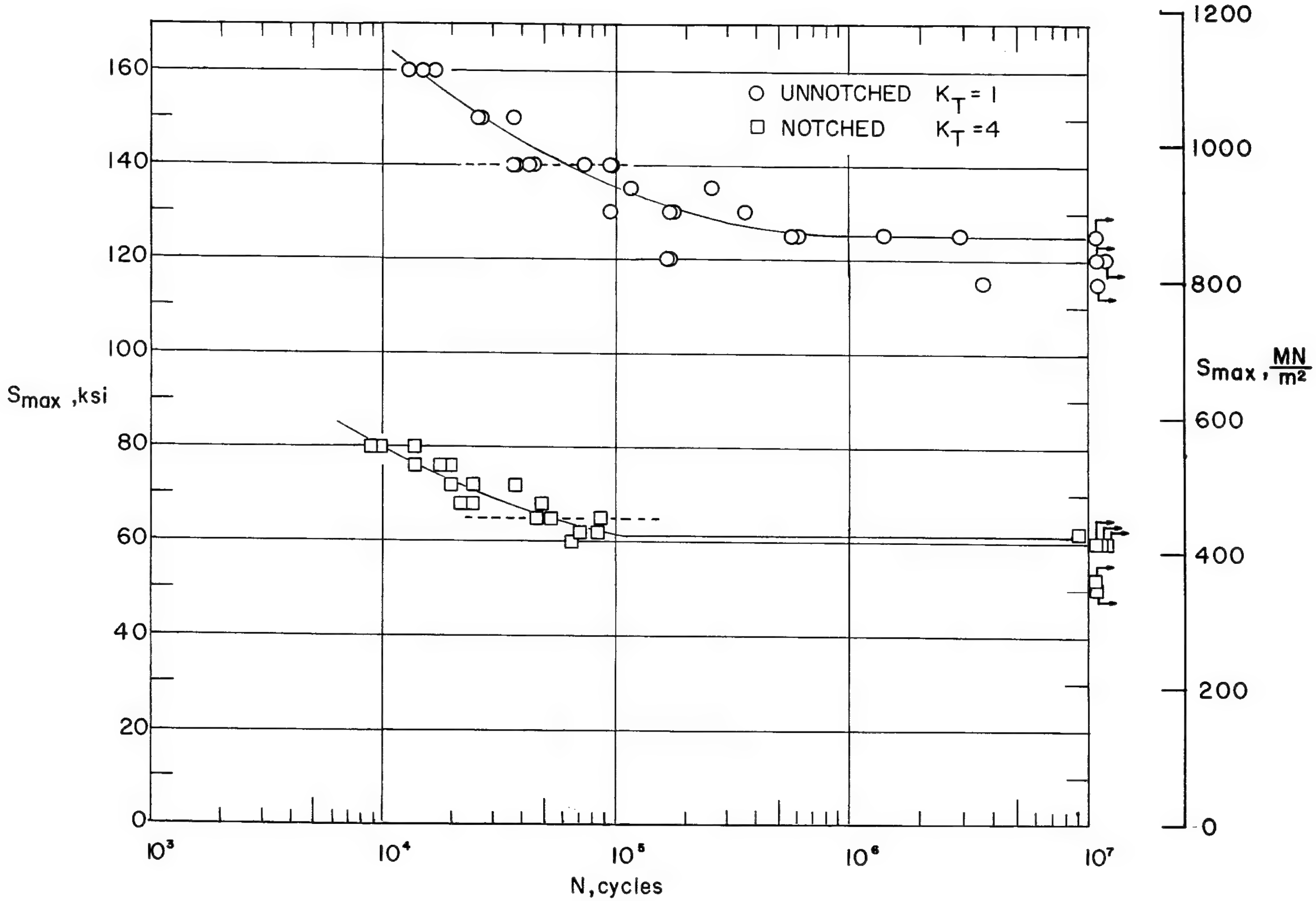
(b) AM 350 20 percent CRT; mean stress, 40 000 psi (276 MN/m^2).

Figure 5.- Continued.



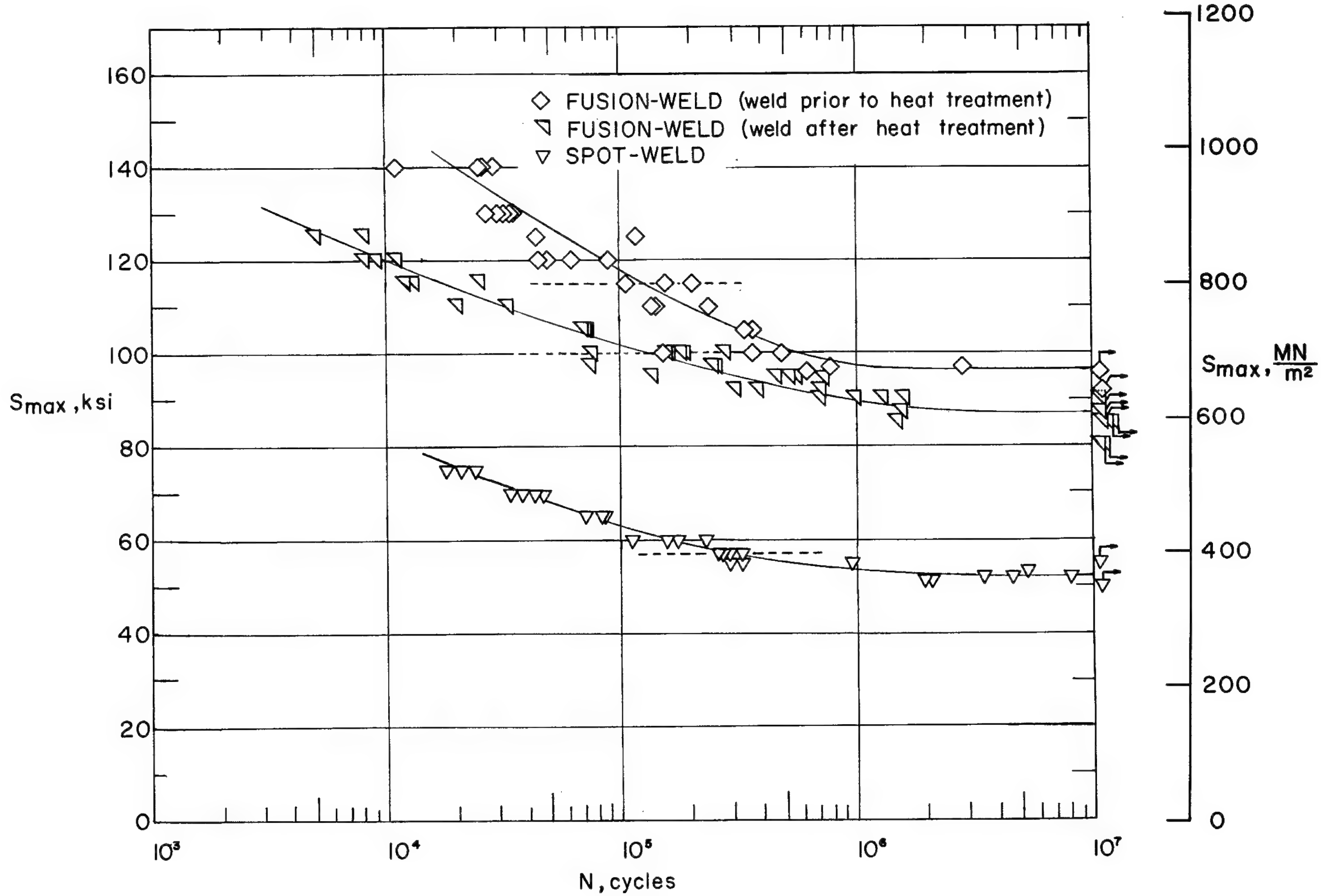
(b) AM 350 20 percent CRT; mean stress, 40 000 psi (276 MN/m^2). Concluded.

Figure 5.- Continued.



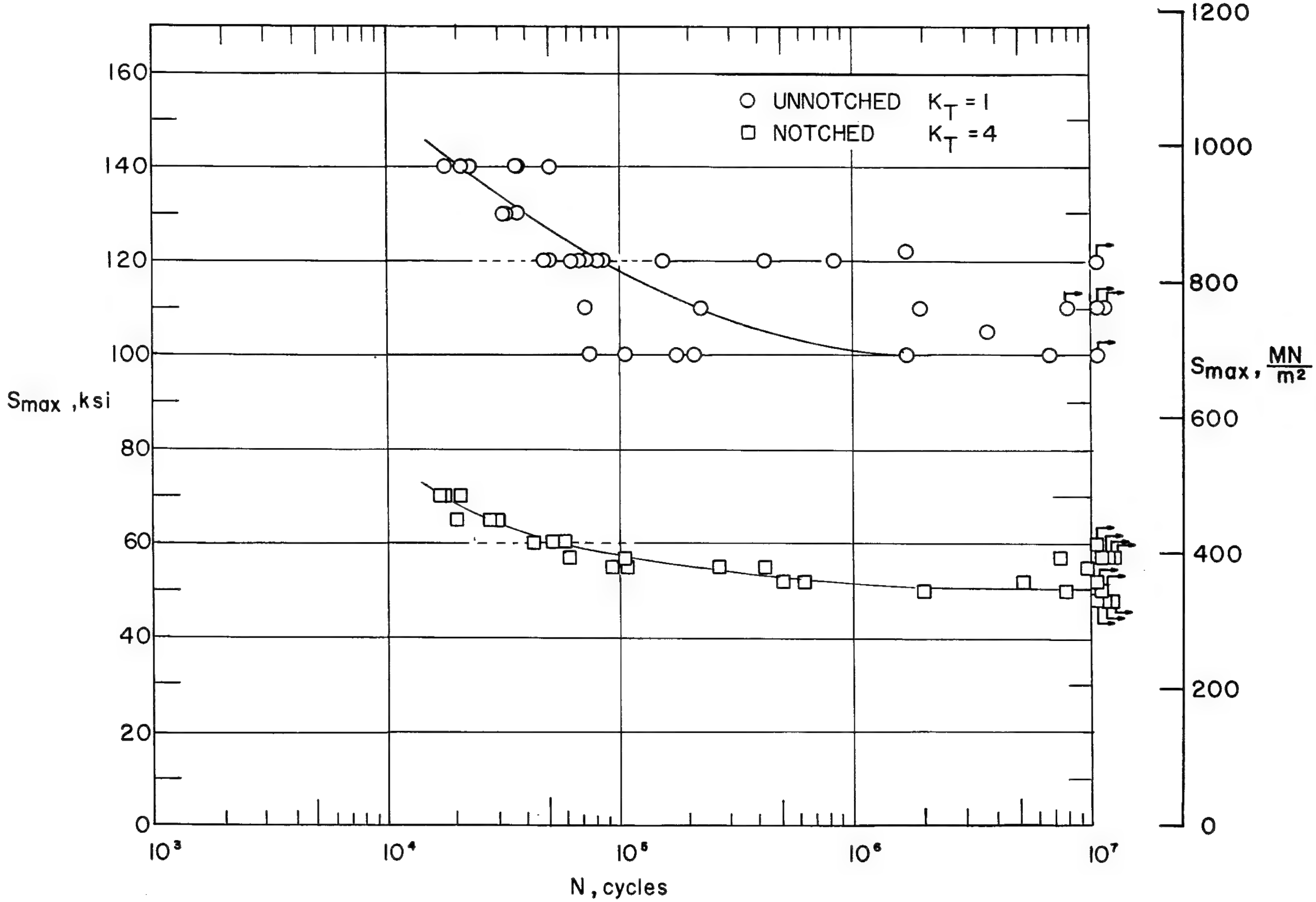
(c) AM 350 double aged; mean stress, 40 000 psi (276 MN/m^2).

Figure 5.- Continued.



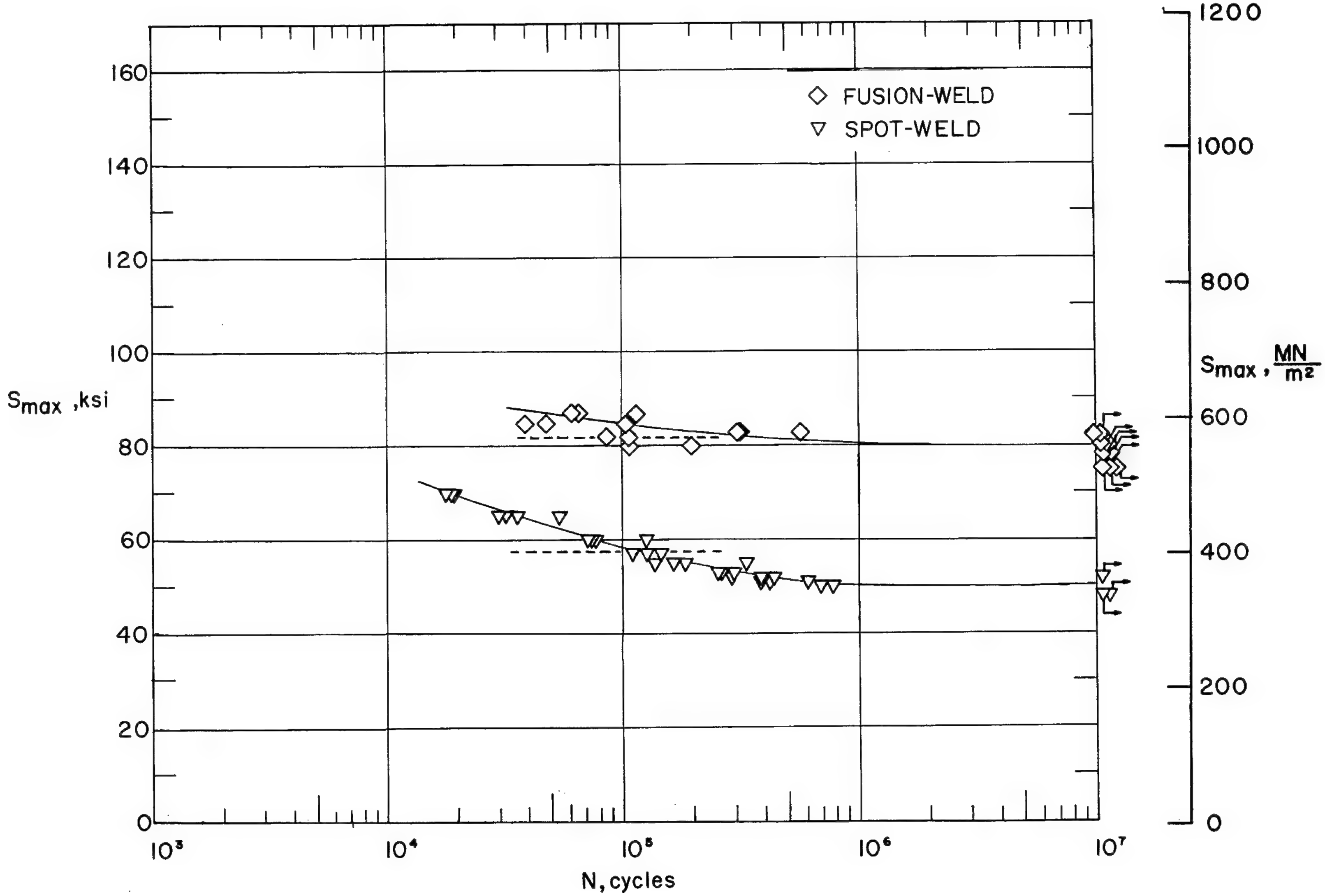
(c) AM 350 double aged; mean stress, 40 000 psi (276 MN/m^2). Concluded.

Figure 5.- Continued.



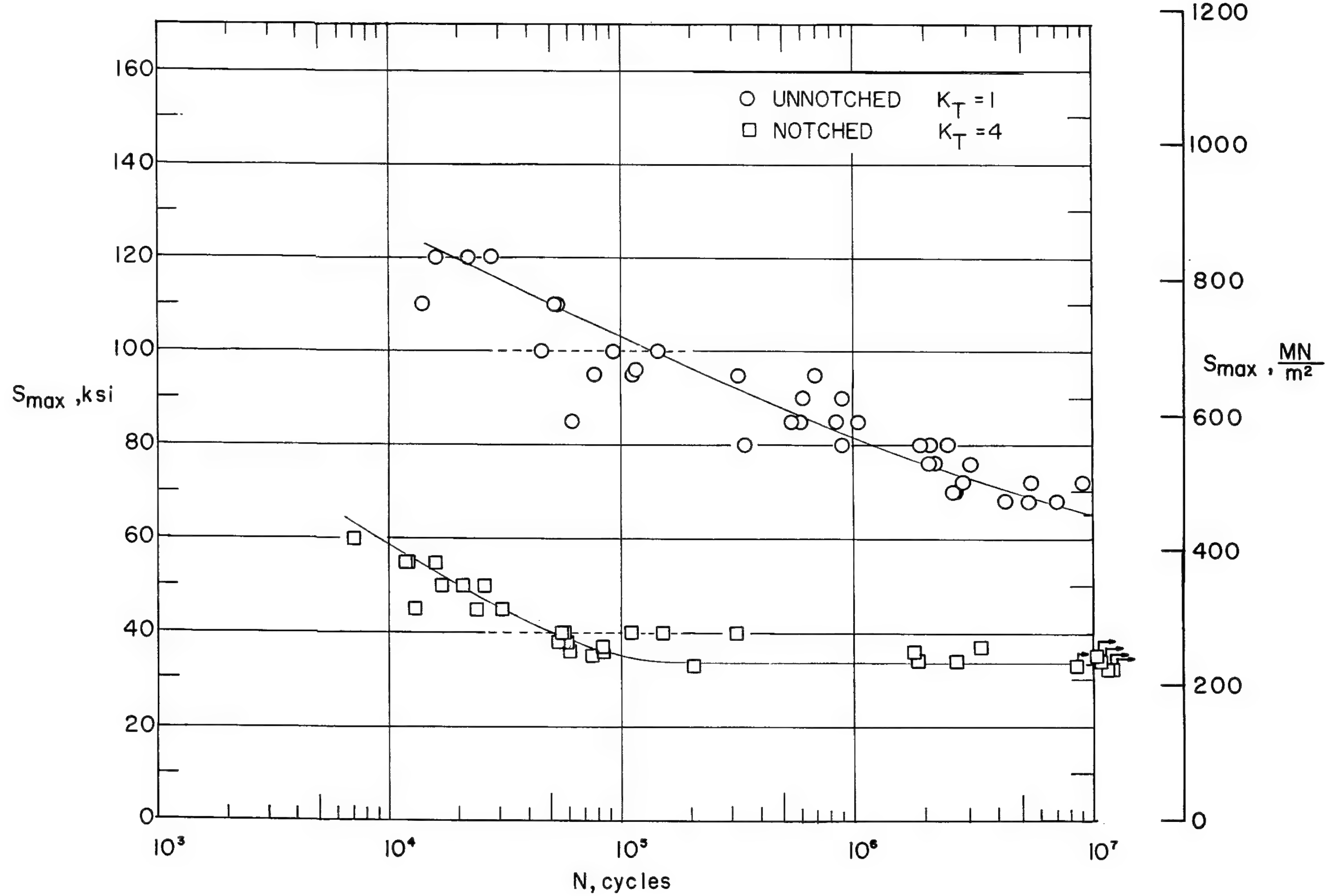
(d) AISI 301 50 percent CR; mean stress, 40 000 psi (276 MN/m^2).

Figure 5.- Continued.



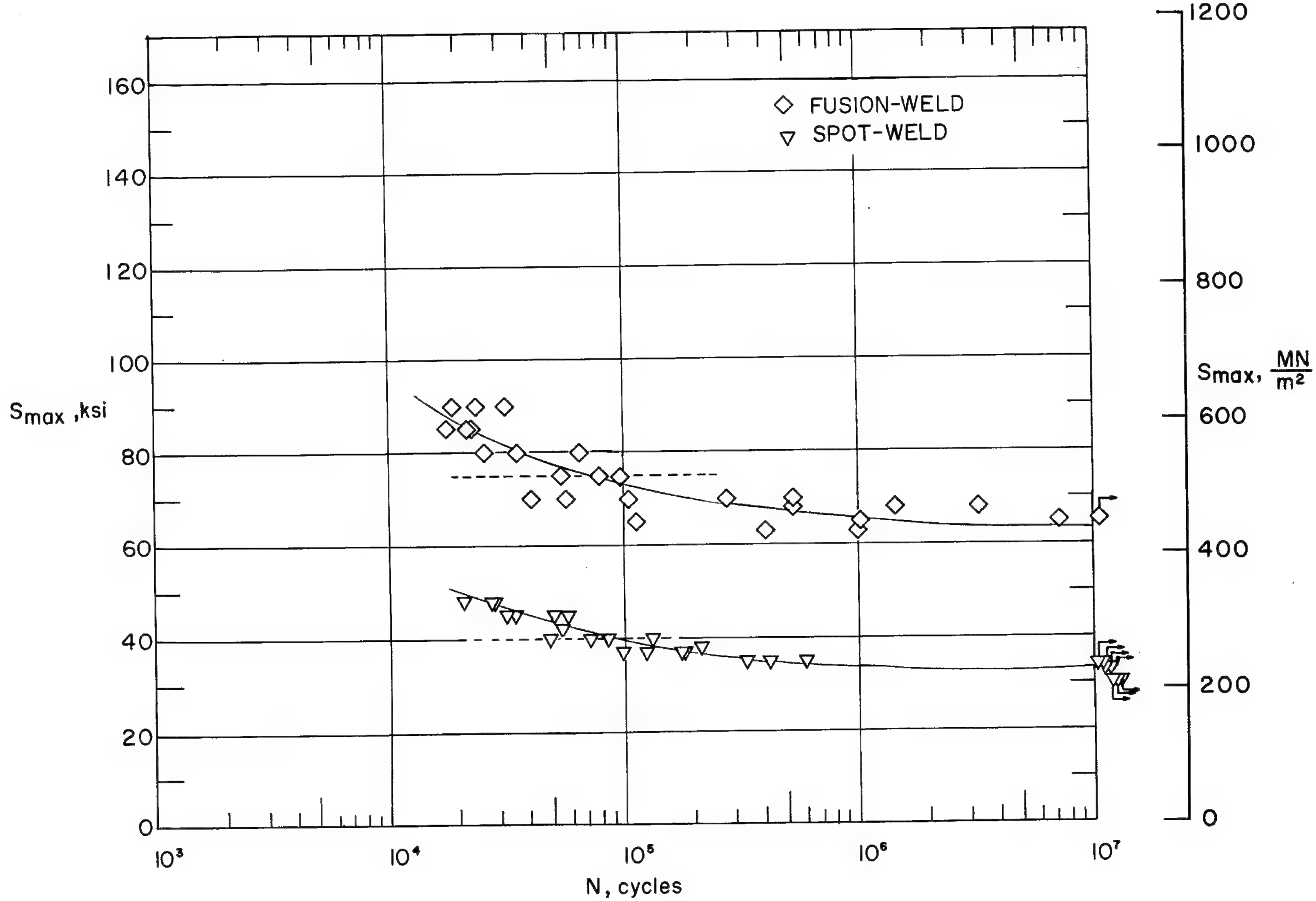
(d) AISI 301 50 percent CR; mean stress, 40 000 psi (276 MN/m^2). Concluded.

Figure 5.- Continued.



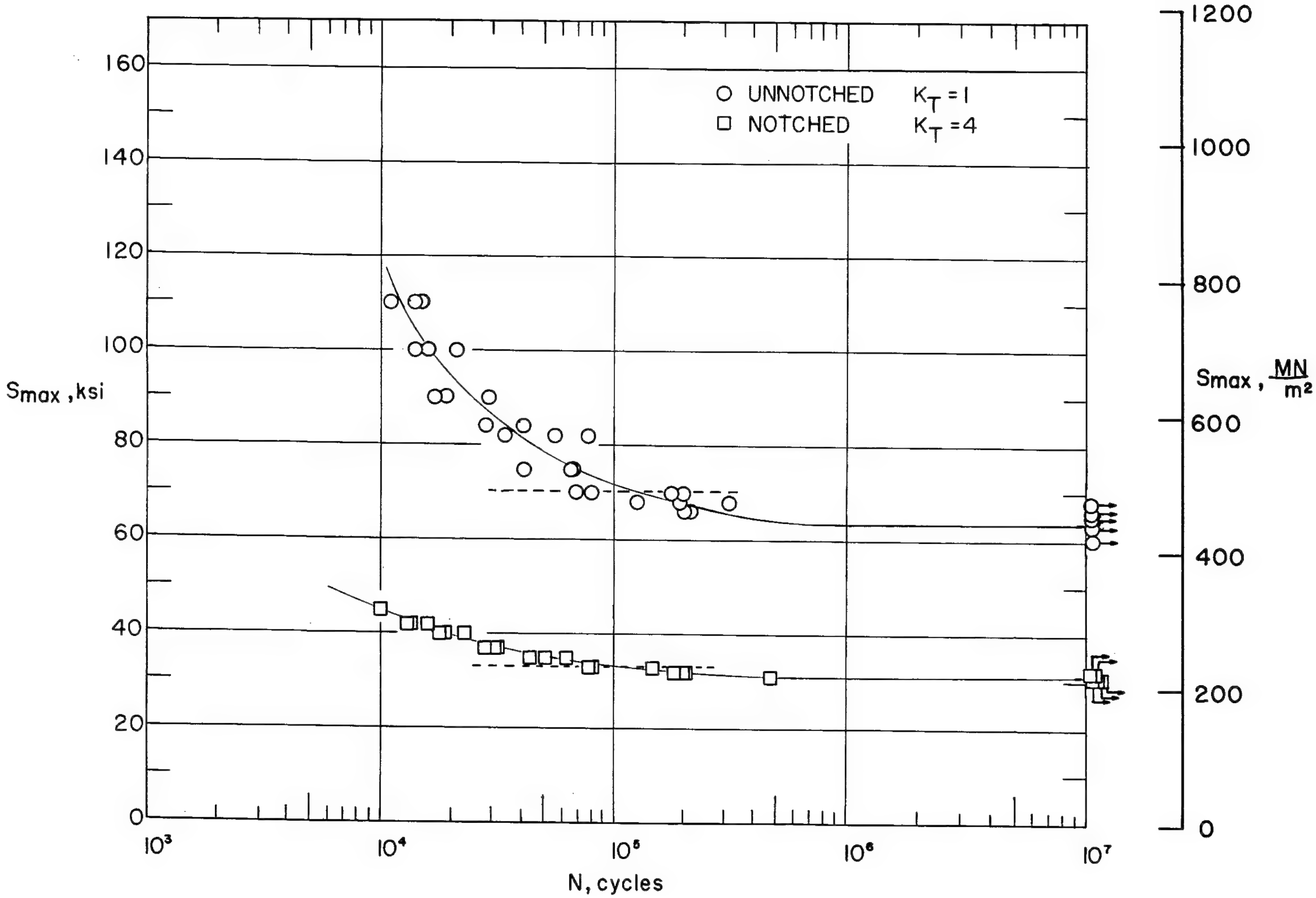
(e) Ti-6Al-4V, annealed; mean stress, 25 000 psi (173 MN/m^2).

Figure 5.- Continued.



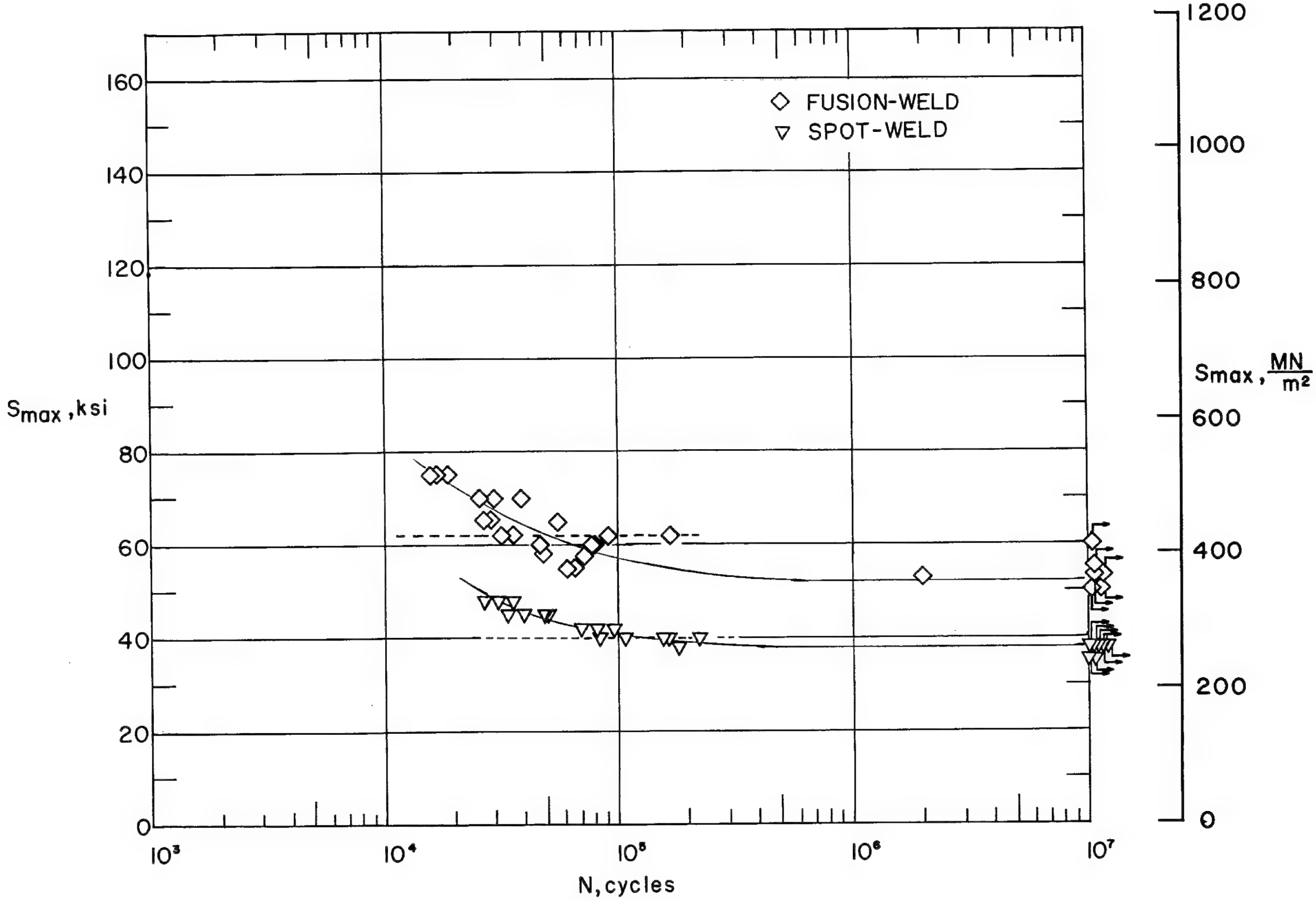
(e) Ti-6Al-4V, annealed; mean stress, 25 000 psi (173 MN/m^2). Concluded.

Figure 5.- Continued.



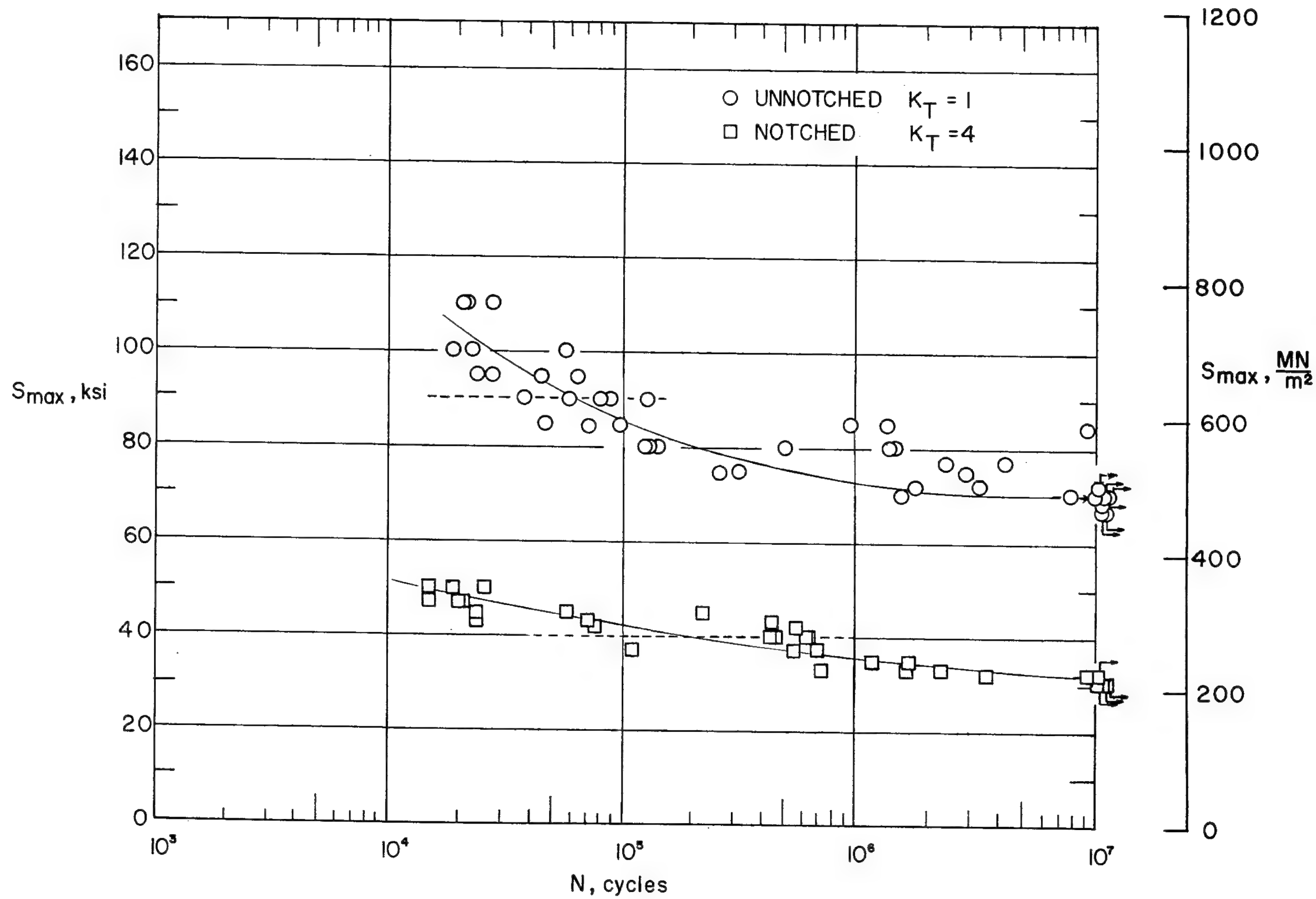
(f) Ti-4Al-3Mo-IV, aged; mean stress, 25 000 psi (173 MN/m²).

Figure 5.- Continued.



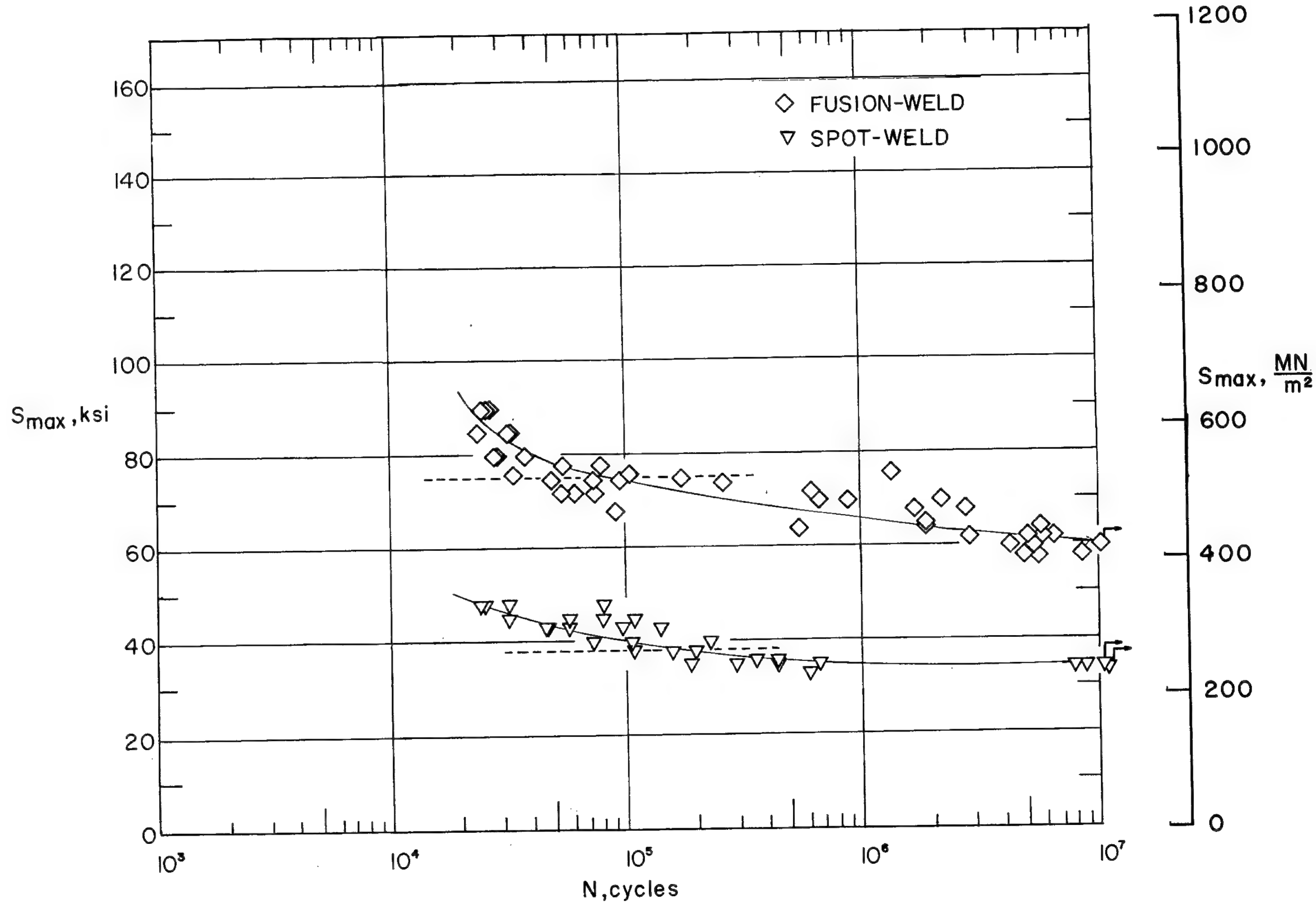
(f) Ti-4Al-3Mo-IV, aged; mean stress, 25 000 psi (173 MN/m^2). Concluded.

Figure 5.- Continued.



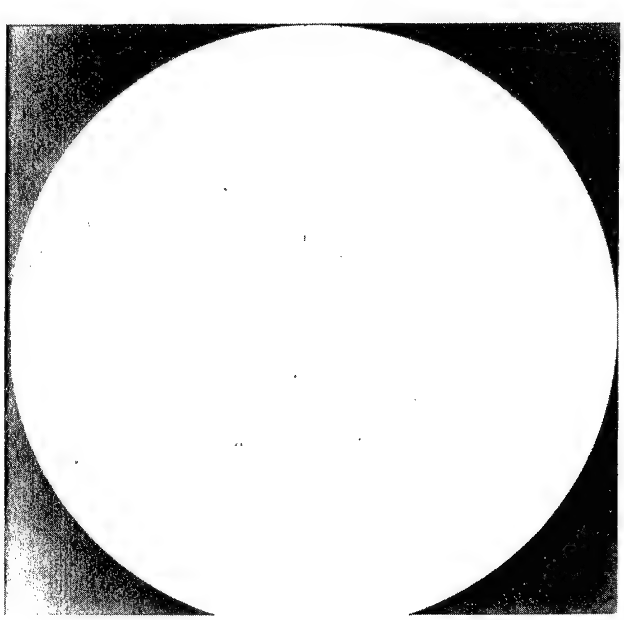
(g) Ti-8Al-1Mo-IV, single annealed; mean stress 25 000 psi (173 MN/m^2).

Figure 5.- Continued.

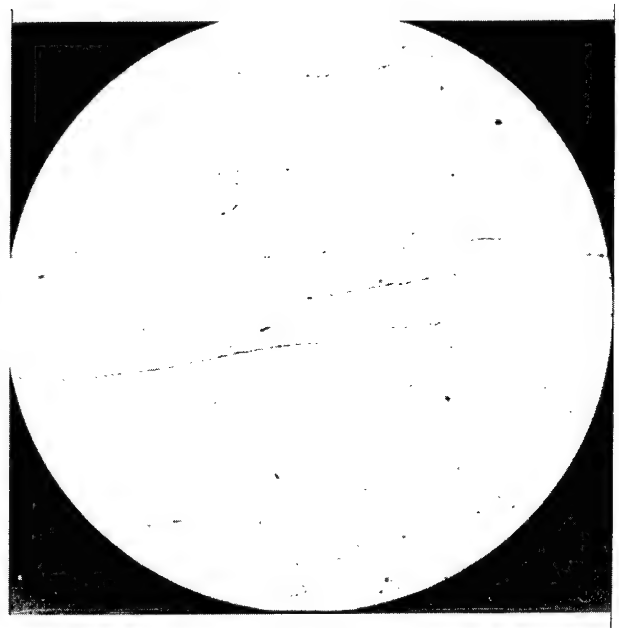


(g) Ti-8Al-1Mo-1V, single annealed; mean stress 25 000 psi (173 MN/m^2). Concluded.

Figure 5.- Concluded.



TRANSVERSE CROSS SECTION



LONGITUDINAL CROSS SECTION

SURFACE

Figure 6.- Photomicrographs of AISI 301 stainless steel 150X. L-65-40

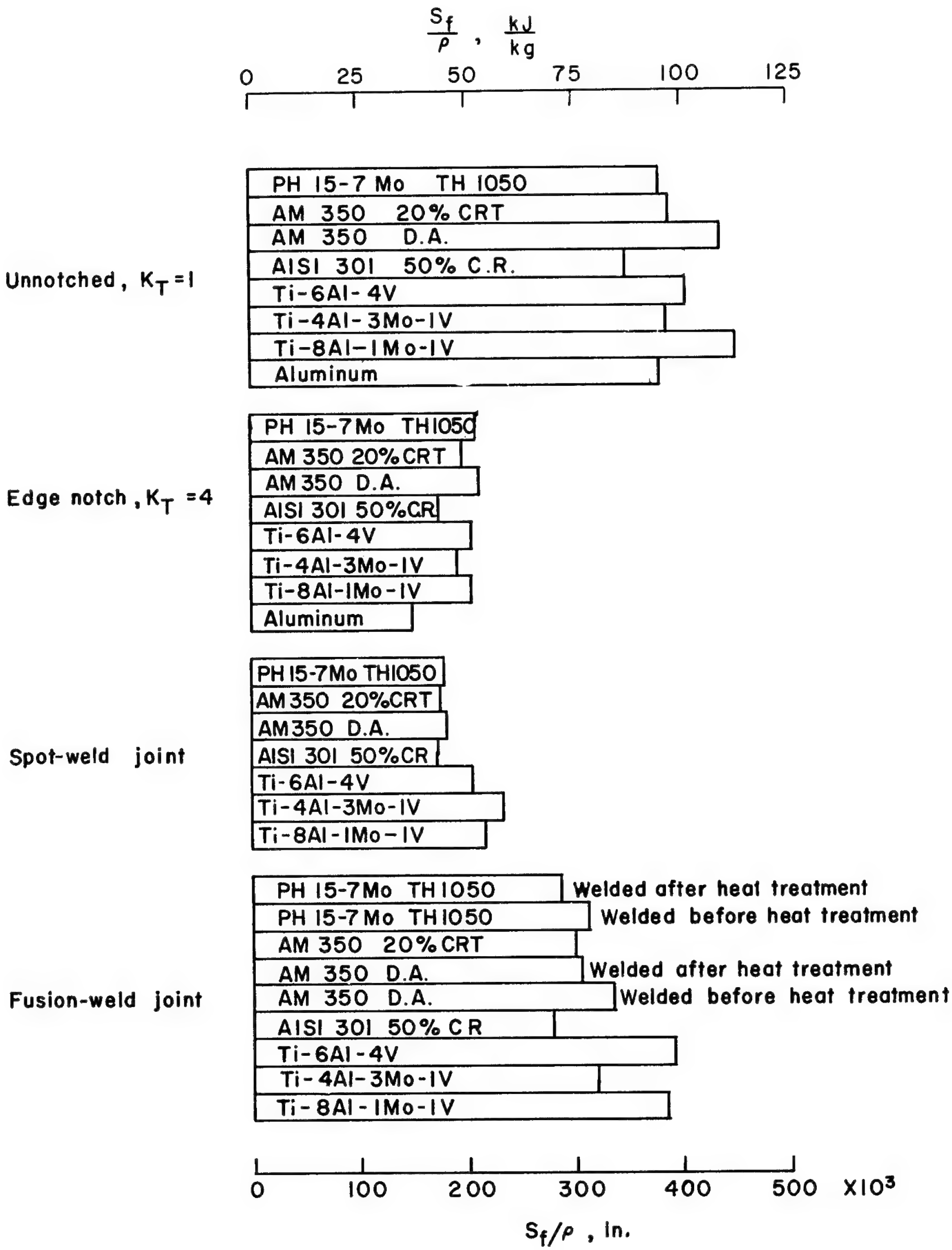
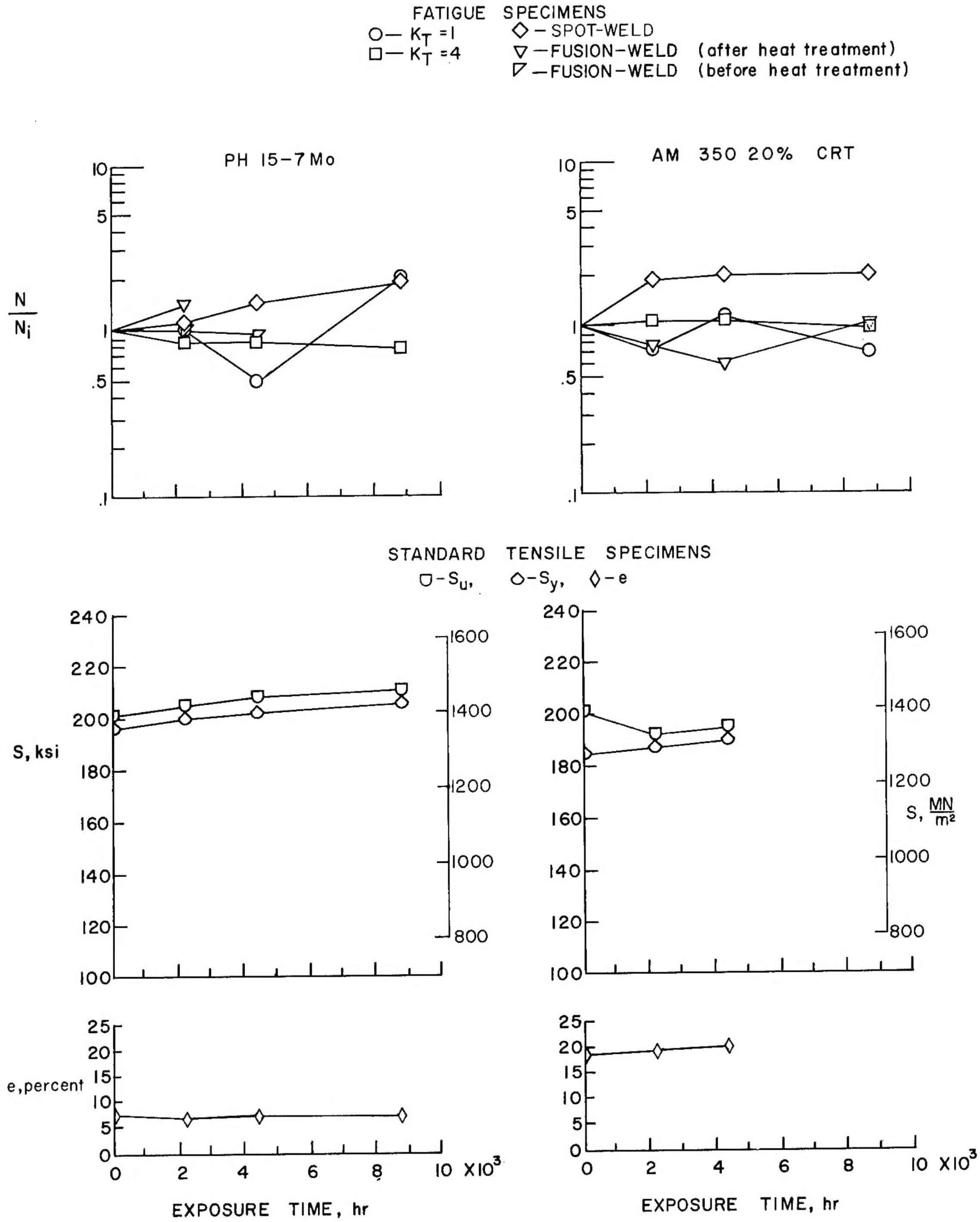
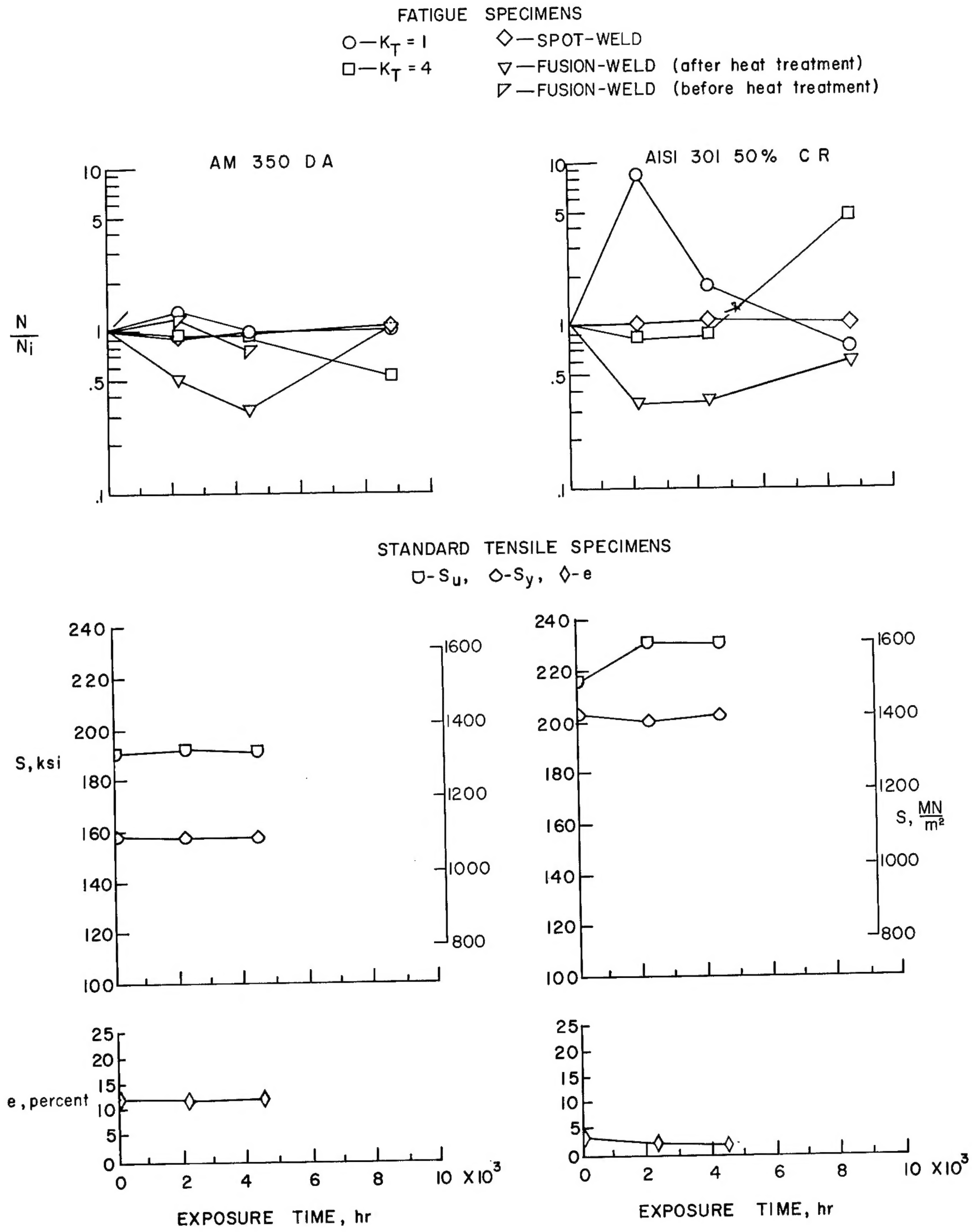


Figure 7.- Comparison of ratios of fatigue limit to density.



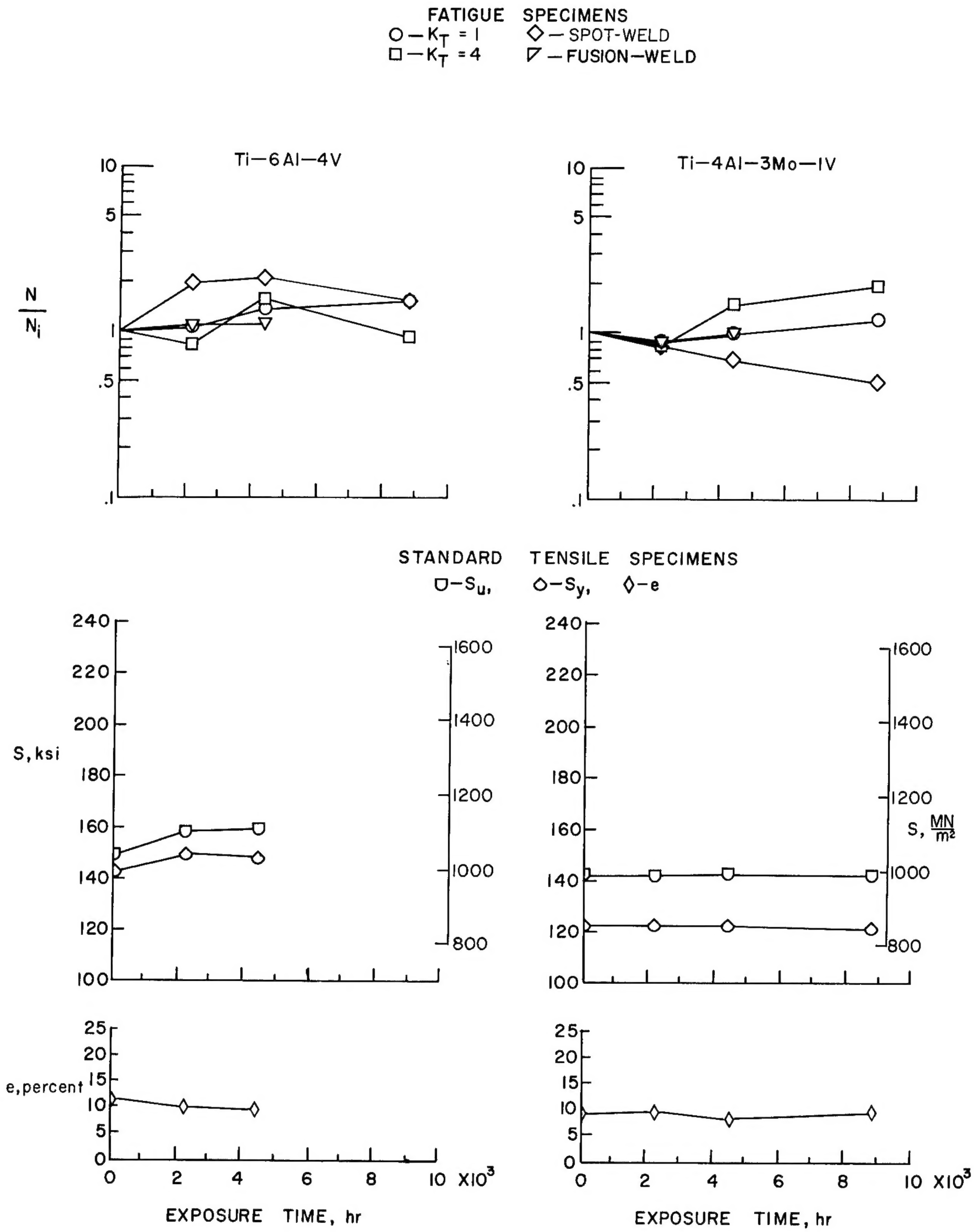
(a) PH 15-7Mo and AM 350 20 percent CRT.

Figure 8.- Results of exposure to 550° F (561° K) on fatigue limit, static strength, and elongation.



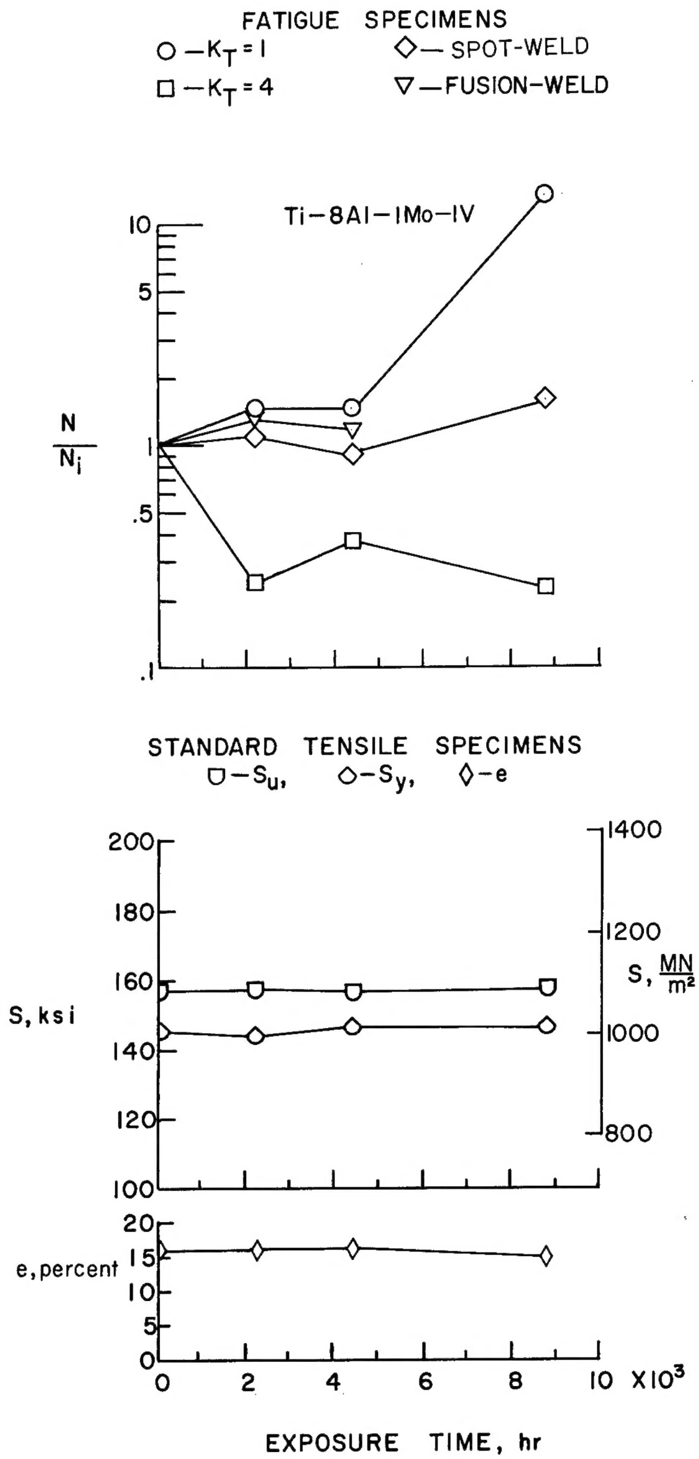
(b) AM 350 double aged and AISI 301 50 percent CR.

Figure 8.- Continued.



(c) Ti-6Al-4V and Ti-4Al-3Mo-1V.

Figure 8.- Continued.



(d) Ti-8Al-1Mo-1V.

Figure 8.- Concluded.